TC 9-62

Communications-Electronics Fundamentals

Solid State Devices and Solid State Power Supplies and Amplifiers

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Communications-Electronics Fundamentals

Solid State Devices and Solid State Power Supplies and Amplifiers

Contents

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Preface

The objective of this TC is to provide a broad coverage of solid state devices and, as a broad application, power supplies. This TC covers the development of the semiconductor, the transistor, special devices, solid state power supplies, and amplifiers. This manual also identifies important safety practices to follow when working with electricity.

Learning objectives are stated at the beginning of each chapter. Check-on-learning questions are included at the end of each chapter. Appendix A (Check-on-Learning Answers) is included to provide answers to the check-on-learning questions from each chapter.

This publication applies to the Active Army, the Army National Guard/Army National Guard of the United States, and the U.S. Army Reserve.

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Chapter 1

Semiconductor Diodes

LEARNING OBJECTIVES

Learning objectives serve as a preview of the information you are expected to learn in this chapter. The comprehensive check-on-learning questions, found at the end of the chapter, are based on the objectives. Upon completion of this chapter, you will be able to perform the following learning objectives:

- State, in terms of energy bands, the differences between a conductor, an insulator, and a semiconductor.
- Explain the electron and the hole flow theory in semiconductors and how the semiconductor is affected and how the semiconductor is affected by doping.
- Define the term "diode" and give a brief description and operation.
- Explain how to use the diode as a half-wave rectifier and as a switch.
- Identify the diode by its symbolism, alphanumerical designation, and color code.
- List the precautions to take when working with diodes and describe the different ways to test them.

INTRODUCTION TO SOLID STATE DEVICES

1-1. Semiconductors have electrical properties somewhere between those of insulators and conductors. The use of semiconductor materials in electronic components is not new. Some devices are as old as the electron tube. Two of the most well known semiconductors in use today are the JUNCTION DIODE and TRANSISTOR. These semiconductors fall under a more general heading called solid state devices. A SOLID STATE DEVICE is nothing more than an electronic device that operates when electrons move within a solid piece of semiconductor material. Since the invention of the transistor, solid state devices have been developed and improved at an incredible rate. Great strides have been made in the manufacturing techniques. There is no foreseeable limit to the future of these devices. Solid state devices made from semiconductor materials offer the following:

- Compactness.
- Efficiency.
- Ruggedness.
- Versatility.

These devices have entered into almost every field of science and industry. In addition to the junction diode and transistor, a whole new family of related devices has been developed. Some of these devices include the ZENER DIODE, LIGHT-EMITTING DIODE, and FIELD EFFECT TRANSISTOR. The development of the IC has dominated solid state technology for the last decade. The IC probably has had a greater impact on the electronics industry than either the electron tube or transistor. The IC is a small piece of semiconductor material that can produce complete electronic circuit functions.

1-2. As the applications of solid state devices increase, the need for knowledge of these devices becomes greater in importance. Army personnel will have to understand solid state devices if they are to become proficient in the repair and maintenance of electronic equipment.

SEMICONDUCTOR DEVELOPMENT

1-3. In l883, Michael Faraday discovered that silver sulfide, a semiconductor, had a negative temperature coefficient. The term negative temperature coefficient is just another way of saying its resistance to electrical current flow decreases as temperature increases. The opposite is true of the conductor (it has a positive temperature coefficient). Because of this particular characteristic, semiconductors are used extensively in power-measuring equipment (see TC 9-60).

1-4. Two years later, Munk A. Rosenshold discovered that certain materials have rectifying properties (the ability to convert AC into DC). His finding was given such little notice that it had to be rediscovered 39 years later by F. Braun.

1-5. Toward the close of the 19th century, experimenters began to notice the strange characteristics of the chemical element SELENIUM. They discovered that in addition to its rectifying properties, selenium was also light sensitive (its resistance decreased with an increase in light intensity). This discovery led to the invention of the photophone by Alexander Graham Bell. The photophone, which converted variations of light into sound, was a predecessor of the radio receiver. It was not until the actual birth of radio that selenium was largely used. Today, selenium is an important and widely used semiconductor.

1-6. Many other materials were tried and tested for use in communications. SILICON, a metallic element, was found to be the most stable of the materials tested while GALENA, a crystallized form of lead sulfide, was found the most sensitive for use in early radio receivers. Carl Beredicks discovered that GERMANIUM, another metallic element, also had rectifying capabilities. It later became widely used in electronics for low-power, low frequency applications.

1-7. Although the semiconductor existed before the electron tube was invented, the semiconductor devices of that time could not match the performance of the tube. Radio needed a device that could not only handle power and amplify, but also rectify and detect a signal as well. Since tubes could do all these things and semiconductor devices of that day could not, the semiconductor was replaced.

1-8. Interest was renewed in the semiconductor at the beginning of World War II. There was an urgent need for a device that could work within the ultra-high frequencies of radar. Electron tubes had interelectrode capacitances that were too high to do the job. However, the point-contact semiconductor diode had a very low internal capacitance. Therefore, it could be designed to work within the ultra-high frequencies used in radar, while the electron tube could not.

1-9. As radar took on greater importance and C-E equipment became more sophisticated, the demands for better solid state devices mounted. The limitations of the electron tube made it necessary to search for something new and different. An amplifying device was needed that was smaller, lighter, more efficient, and capable of handling extremely high frequencies. If progress was to be made, these requirements had to be met. A serious study of semiconductor materials began in the early 1940's and has continued to the present.

1-10. The discovery of the POINT-CONTACT TRANSISTOR in June 1948 was a significant breakthrough in semiconductor development. Here was a semiconductor that could amplify. This discovery brought the semiconductor back into competition with the electron tube. A year later, JUNCTION DIODES and TRANSISTORS were developed. The junction transistor was found superior to the point-contact type in many respects. By comparison, the junction transistor was more reliable, generated less noise, and had higher power-handling ability than the point-contact type. The junction transistor became a rival of the electron tube in many uses previously uncontested.

1-11. Semiconductor diodes were not to be slighted. The initial work of Dr. Carl Zener led to the development of the ZENER DIODE, which is often used today to regulate power supply voltages at precise levels. More interest in the solid state diode was generated when Dr. Leo Esaki, a Japanese scientist, fabricated a diode that could amplify. This device, named the TUNNEL DIODE, has amazing gain and fast switching capabilities. Although it is used in the conventional amplifying and oscillating circuits, its primary use is in computer logic circuits.

1-12. Another discovery in the late 1950's was that semiconductor materials could be combined and treated so that they functioned as an entire circuit or subassembly rather than as a circuit component. Many names have been given to this solid-circuit concept, such as INTEGRATED CIRCUITS, MICROELECTRONICS, and MICROCIRCUITRY.

SEMICONDUCTOR APPLICATIONS

1-13. The use of semiconductor devices has become so widespread that it would be impossible to list all their different applications. Instead, a broad coverage of their specific application is presented.

1-14. Semiconductor devices can be found in just about every commercial product we use (from the family car to the pocket calculator). Semiconductor devices have even found their way into television sets, portable radios, and stereo equipment.

1-15. Science and industry also rely heavily on semiconductor devices. Research laboratories use these devices in all sorts of electronic instruments to perform tests, measurements, and many other experimental tasks. Industrial control systems (such as those used to manufacture automobiles) and automatic telephone exchanges also use semiconductors. Even heavy-duty versions of the solid state rectifier diode are being used today to convert large amounts of power for electric railroads. Of the many different applications for solid state devices; space systems, computers, and data processing equipment are some of the largest consumers.

1-16. Many types of modern military equipment are literally loaded with semiconductor devices. Many radar, communication, and airborne equipment are transistorized. Data display systems, data processing units, computers, and aircraft guidance-control assemblies are also good examples of electronic equipment that use semiconductor devices. All of the specific applications of semiconductor devices would make a long impressive list.

Semiconductors are now being used extensively in commercial products, industry, and all branches of the armed services.

SEMICONDUCTOR COMPETITION

1-17. Semiconductor devices can and do perform all the conventional functions of rectification, amplification, oscillation, timing, switching, and sensing. These devices perform the same basic functions as the electron tube but perform more efficiently, economically, and for a longer period of time. Therefore, it should be no surprise to see these devices used in place of electron tubes. Keeping this in mind, we see that it is only natural and logical to compare semiconductor devices with electron tubes.

1-18. Semiconductor devices are physically much smaller than tubes. Figure 1-1 shows some commonly used tube sizes alongside semiconductor devices of similar capabilities. The reduction in size can be as great as 100:1 by weight and 1,000:1 by volume. It is easy to see that size reduction favors the semiconductor device. Therefore, whenever miniaturization is required or is convenient, transistors are favored over tubes. However, that the extent of practical size reduction is a big factor; many other things must be considered. For example, miniature electron tubes may be preferred in certain applications to transistors, thereby keeping size reduction a competitive area.

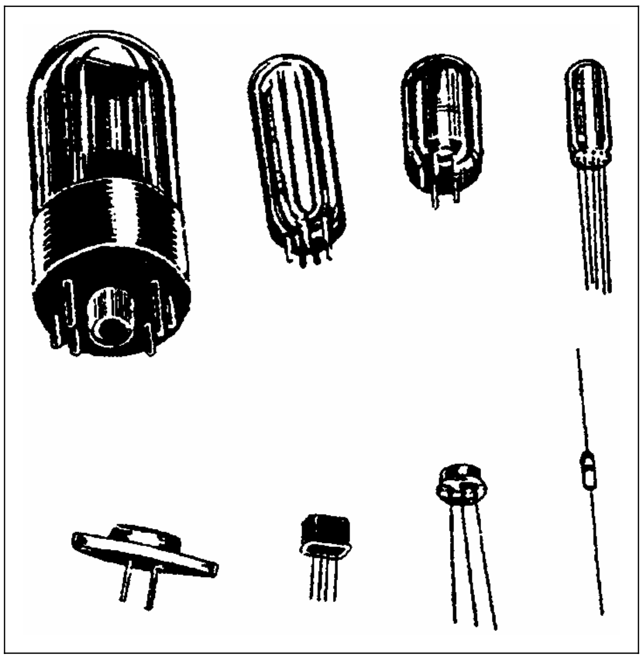


Figure 1-1. Size Comparisons of Electron Tubes and Semiconductors

1-19. For low-power applications, where efficiency is a significant factor, semiconductors have a decided advantage. This is true mainly because semiconductor devices perform very well with an extremely small amount of power. They also require no filaments or heaters, as in the case of the electron tube. For example, a computer operating with over 4,000 solid state devices may require no more than 20 watts of power. However, the same number of tubes would require several kilowatts of power.

1-20. For high-power applications, tubes have a decided advantage. The high-power electron tube has no equivalent in any semiconductor device. This is because a tube can be designed to operate with over a thousand volts applied to its plate while the maximum

allowable voltage for a transistor is limited to about 200 volts (usually 50 volts or less). A tube can also handle thousands of watts of power. The maximum power output for transistors generally ranges from 30 milliwatts to slightly over 100 watts.

1-21. When it comes to ruggedness and life expectancy, the tube is still in competition. Design and functional requirements usually dictate the choice of devices. However, semiconductor devices are rugged and long-lived. They can be constructed to withstand extreme vibration and mechanical shock. They have been known to withstand impacts that would completely shatter an ordinary electron tube. Although some specially designed tubes render extensive service, the life expectancy of transistors is better than three to four times that of ordinary electron tubes. There is no known failure mechanism (such as an open filament in a tube) to limit the semiconductor's life. However, semiconductor devices do have some limitations. They are usually affected more by temperature, humidity, and radiation than are tubes.

MATTER AND ENERGY

1-22. To understand why solid state devices function as they do, we will have to examine the composition and nature of semiconductors. This entails theory that is fundamental to the study of solid state devices. Rather than beginning with theory, let us first become reacquainted with some of the basic information concerning matter and energy.

ATOMIC STRUCTURE

1-23. The universe, as we know it today, is divided into two parts, matter and energy. Matter, is anything that occupies space and has weight. Rocks, water, air, automobiles, clothing, and even our own bodies are good examples of matter. From this, we can conclude that matter may be found in any one of the following three states:

- Solid.
- Liquid.
- Gaseous.

All matter is composed of either an element or combination of elements. An element is a substance that cannot be reduced to a simpler form by chemical means. Examples of elements with which you are in contact with every day are iron, gold, silver, copper, and oxygen. Presently, matter consists of over 100 known elements.

1-24. As we work our way down the size scale, we come to the atom, the smallest particle into which an element can be broken down and still retain all its original properties. However, the atom of one element differs from the atoms of all other elements. Since there are over 100 known elements, there must be over 100 different atoms, or a different atom for each element.

1-25. Let us consider more than one element at a time. This brings us to the term, “compound.” A compound is a chemical combination of two or more elements. Water, table salt, ethyl alcohol, and ammonia are all examples of compounds. The smallest part of a compound, which has all the characteristics of the compound, is the molecule. Each molecule contains some of the atoms of each of the elements forming the compound.

1-26. Let us consider sugar. Sugar in general terms is matter, since it occupies space and has weight. It is also a compound because it consists of two or more elements. Take a lump of sugar and crush it into small particles; each of the particles still retains its original

identifying properties of sugar. The only thing that changed was the physical size of the sugar. If we continue this subdividing process by grinding the sugar into a fine powder, the results are the same. Even dissolving the sugar in water does not change its identifying properties, in spite of the fact that the particles of sugar are now too small to see even with a microscope. Eventually, we end up with a quantity of sugar, which cannot be further divided without it ceasing to be sugar. This quantity is known as a molecule of sugar. If the molecule is further divided, it is found to consist of three simpler kinds of matter: carbon, hydrogen, and oxygen. These simpler forms are called elements. Therefore, since elements consist of atoms, then a molecule of sugar is made up of atoms of carbon, hydrogen, and oxygen.

1-27. As we examine the atom, we find that it is basically composed of electrons, protons, and neutrons. The electrons, protons, and neutrons of one element are identical to those of any other element. However, there are different kinds of elements because the number and the arrangement of electrons and protons are different for each element.

1-28. The electron is considered to be a small negative charge of electricity. The proton has a positive charge of electricity equal and opposite to the charge of the electron. Scientists have measured the mass and size of the electron and proton and they know how much charge each possesses. The electron and proton have the same quantity of charge, although the mass of the proton is approximately 1,837 times that of the electron. In some atoms there exists a neutral particle called a neutron. The neutron has a mass approximately equal to that of a proton, but it has no electrical charge.

1-29. According to a popular theory, the arrangement of electrons, protons, and neutrons of an atom is similar to a miniature solar system. Notice the helium atom in Figure 1-2. Two protons and two neutrons form the heavy nucleus with a positive charge around which two very light electrons revolve. The path each electron takes around the nucleus is called an orbit. The electrons are continuously being acted upon in their orbits by the force of attraction of the nucleus. To maintain an orbit around the nucleus, the electrons travel at a speed that produces a counterforce equal to the attraction force of the nucleus. Just as energy is required to move a space vehicle away from the earth, energy is also required to move an electron away from the nucleus. Like a space vehicle, the electron is said to be at a higher energy level when it travels a larger orbit. Scientific experiments show that the electron requires a certain amount of energy to stay in orbit. This quantity is called the electron's energy level. By virtue of just its motion alone, the electron contains kinetic energy. Due to its position, it also contains potential energy. The total energy contained by an electron (kinetic energy plus potential energy) is the main factor that determines the radius of the electron's orbit. In order for an electron to remain in this orbit, it must neither gain nor lose energy.

1-30. The orbiting electrons do not follow random paths; instead they are confined to definite energy levels. Picture these levels as shells with each successive shell being spaced a greater distance from the nucleus. The shells, and the number of electrons required to fill them, may be predicted by using Pauli's exclusion principle. Simply stated, this principle specifies that each shell will contain a maximum of $2n^2$ electrons, where “n” corresponds to the shell number starting with the one closest to the nucleus. By this principle, the second shell, for example, would contain $2(2)^2$ or 8 electrons when full.

1-31. In addition to being numbered, the shells are also given letter designations starting with the shell closest to the nucleus and progressing outward (see Figure 1-3). The shells are considered to be full, or complete, when they contain the following quantities of electrons: two in the K(1st) shell, eight in the L(2nd) shell, eighteen in the M(3rd) shell,

and so on, in accordance with the exclusion principle. Each of these shells is a major shell and can be divided into subshells, of which there are four, labeled “s”, “p”, “d”, and “f”. Like the major shells, the subshells are also limited as to the number of electrons that they contain. So, the “s” subshell is complete when it contains two electrons, the “p” subshell when it contains six, the “d” subshell when it contains ten, and the “f” subshell when it contains fourteen electrons.

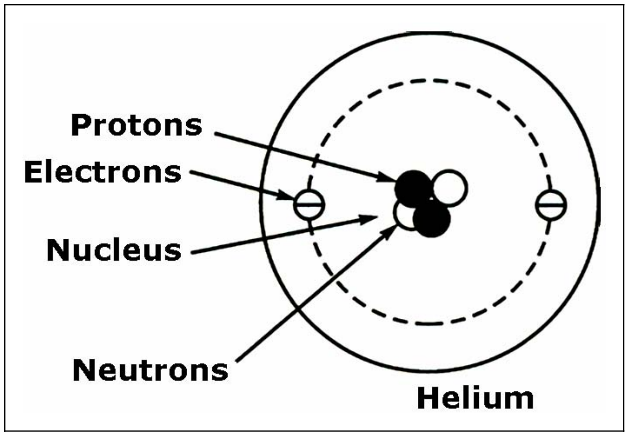


Figure 1-2. Composition of a Simple Helium Atom

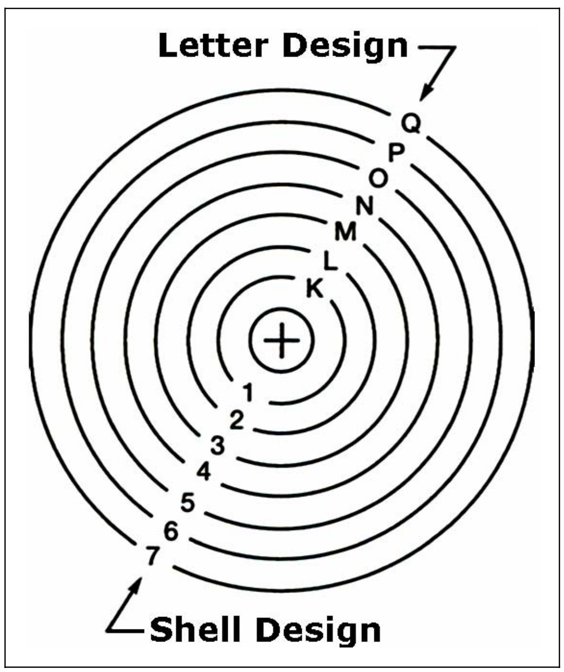


Figure 1-3. Shell Designation

1-32. Since the “K” shell can contain no more than two electrons, it must have only one subshell, the “s” subshell. The “M” shell is composed of three subshells: “s”, “p”, and “d”. If the electrons in the “s”, “p”, and “d” subshells were added together, their total would be 18, the exact number required to fill the “M” shell. Figure 1-4 shows the electron configuration for copper. The copper atom contains 29 electrons, which completely fills the first three shells and subshells, leaving one electron in the “s” subshell of the “N” shell.

A list of all the other known elements, with the number of electrons in each atom, is shown in Appendix B (Periodic Table of Elements).

1-33. Valence is an atom's ability to combine with other atoms. The number of electrons in the outermost shell of an atom determines its valence. Therefore, the outer shell of an atom is called the VALENCE SHELL and the electrons contained in this shell are called VALENCE ELECTRONS. The valence of an atom determines its ability to gain or lose an electron, which in turn determines the chemical and electrical properties of the atom. An atom that is lacking only one or two electrons from its outer shell will easily gain electrons to complete its shell. However, a large amount of energy is required to free any of its electrons. An atom having a relatively small number of electrons in its outer shell in comparison to the number of electrons required to fill the shell will easily lose these valence electrons. The valence shell always refers to the outermost shell.

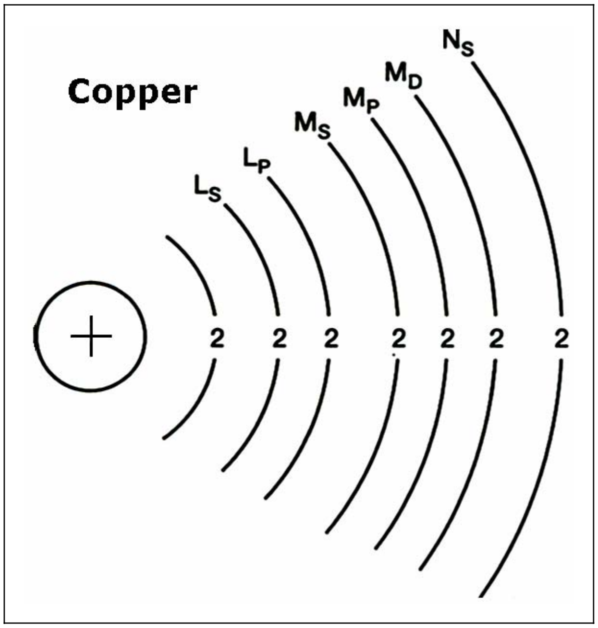


Figure 1-4. Copper Atom

ENERGY BANDS

1-34. Remember, orbiting electrons contain energy and are confined to definite energy levels. The various shells in an atom represent these energy levels. Therefore, in order to move an electron from a lower shell to a higher shell a certain amount of energy is required. This energy can be in the form of electric fields, heat, light, and even bombardment by other particles. Failure to provide enough energy to the electron, even if the energy supplied is just short of the required amount, will cause it to remain at its present energy level. Supplying more energy than is needed will only cause the electron to move to the next higher shell and the remaining energy will be wasted. In simpler terms, energy is required in definite units to move electrons from one shell to the next higher shell. These units are called QUANTA (for example, 1, 2, or 3 quanta).

1-35. Electrons can also lose energy as well as receive it. When an electron loses energy, it moves to a lower shell. The lost energy, in some cases, appears as heat.

1-36. If an electron absorbs a sufficient amount of energy, it is possible for that electron to be completely removed from the influence of the atom. This is called IONIZATION. It is said that an atom is ionized when it loses electrons or gains electrons in this process of electron exchange. For ionization to take place, there must be a transfer of energy that results in a change in the internal energy of the atom. An atom having more than its normal amount of electrons acquires a negative charge and is called a NEGATIVE ION. The atom that gives up some of its normal electrons is left with fewer negative charges than positive charges and is called a POSITIVE ION. Therefore, we can define ionization as the process by which an atom loses or gains electrons.

1-37. So far we have covered only isolated atoms. When atoms are spaced far enough apart, as in a gas, they have very little influence upon each other and are very much like lone atoms. However, atoms within a solid have a marked affect upon each other. The forces that bind these atoms together greatly modify the behavior of the other electrons. One result of this close proximity of atoms is to cause the individual energy levels of an atom to break up and form bands of energy. Discrete (separate and complete) energy levels still exist within these energy bands. However, there are many more energy levels than there were with the isolated atom. In some cases, energy levels will have disappeared. Figure 1-5 shows the difference in the energy arrangement between an isolated atom and the atom in a solid. Notice that the isolated atom (such as in gas) has energy levels while the atom in a solid has energy levels grouped into ENERGY BANDS.

1-38. The upper band in Figure 1-5 is called the CONDUCTION BAND because electrons in this band are easily removed by the application of external electric fields. Materials that have a large number of electrons in the conduction band act as good conductors of electricity.

1-39. Below the conduction band is the FORBIDDEN BAND or energy gap. Electrons are never found in this band. However, they may travel back and forth through it, provided they do not come to rest in the band.

1-40. The bottom band or VALENCE BAND is composed of a series of energy levels containing valence electrons. Electrons in this band are more tightly bound to the individual atom than the electrons in the conduction band. However, the electrons in the valence band can still be moved to the conduction band with the application of energy (usually thermal energy). There are more bands below the valence band but they are not important to the understanding of semiconductor theory.

1-41. The concept of energy bands is particularly important in classifying materials as conductors, semiconductors, and insulators. An electron can exist in either of two energy bands (the conduction band or the valence band). All that is necessary to move an electron from the valence band to the conduction band, so it can be used for electric current, is enough energy to carry the electron through the forbidden band. The width of the forbidden band or the separation between the conduction and valence bands determines whether a substance is an insulator, semiconductor, or conductor. Figure 1-6 uses energy level diagrams to show the difference between insulators, semiconductors, and conductors.

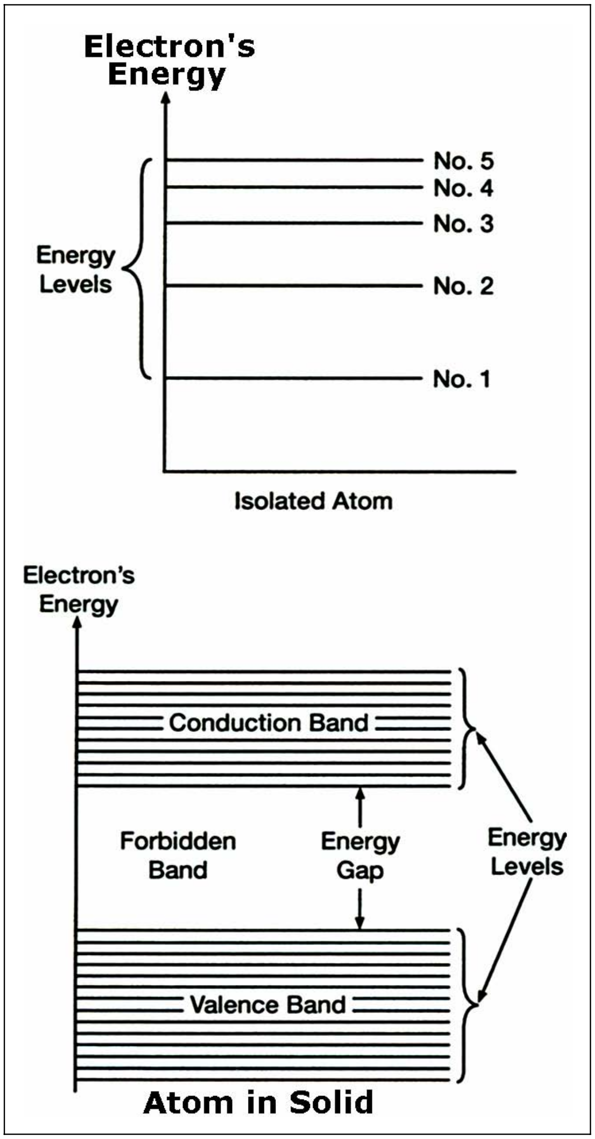


Figure 1-5. Energy Arrangements in Atoms

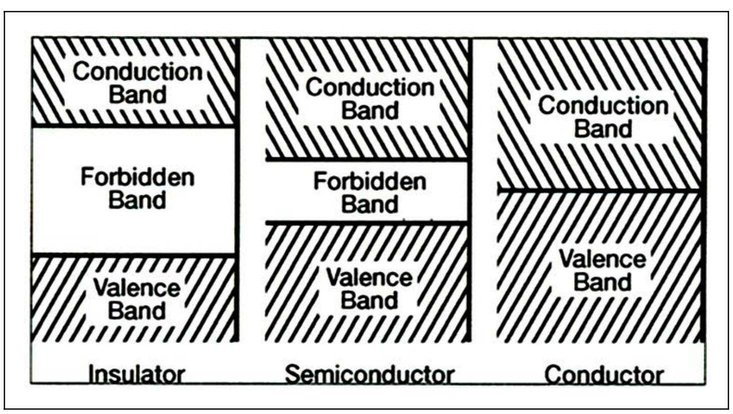


Figure 1-6. Energy Level Diagrams

1-42. The energy diagram for the insulator shows the insulator with a very wide energy gap. The wider the gap, the greater the amount of energy required moving the electron from the valence band to the conduction band. Therefore, an insulator requires a large amount of energy to obtain a small amount of current. The insulator “insulates” because of the wide forbidden band or energy gap.

1-43. The semiconductor has a smaller forbidden band and requires less energy to move an electron from the valence band to the conduction band. Therefore, for a certain amount of applied voltage, more current will flow in the semiconductor than in the insulator.

1-44. The last energy level diagram (see Figure 1-6) is that of a conductor. Notice that there is no forbidden band or energy gap and the valence and conduction bands overlap. With no energy gap, it only takes a small amount of energy to move electrons into the conduction band. Consequently, conductors pass electrons very easily.

COVALENT BONDING

1-45. The number of electrons in its valence shell determines the chemical activity of an atom. When the valence shell is complete, the atom is stable and shows little tendency to combine with other atoms to form solids. Only atoms that possess eight valence electrons have a complete outer shell. These atoms are referred to as inert or inactive atoms. However, if the valence shell of an atom is short the required number of electrons to complete the shell, then the activity of the atom increases.

1-46. For example, silicon and germanium are the most frequently used semiconductors. Both are quite similar in their structure and chemical behavior. Each has four electrons in the valence shell. Consider just silicon. Since it has fewer than the required number of eight electrons needed in the outer shell, its atoms will unite with other atoms until eight electrons are shared. This gives each atom a total of eight electrons in its valence shell; four of its own and four that it borrowed from the surrounding atoms. The sharing of valence electrons between two or more atoms produces a COVALENT BOND between the atoms. It is this bond that holds the atoms together in an orderly structure called a CRYSTAL. A crystal is just another name for a solid whose atoms or molecules are arranged in a three-dimensional geometrical pattern commonly referred to as a lattice. Figure 1-7 shows a typical crystal structure. Each sphere in the figure represents the nucleus of an atom. The arms that join the atoms and support the structure are the covalent bonds.

1-47. As a result of this sharing process, the valence electrons are held tightly together. Figure 1-8 shows a two-dimensional view of the silicon lattice. The circles in the figure represent the nuclei of the atoms. The +4 in the circles is the net charge of the nucleus plus the inner shells (minus the valence shell). The short lines indicate valence electrons. Since every atom in this pattern is bonded to four other atoms, then the electrons are not free to move within the crystal. As a result of this bonding, pure silicon and germanium are poor conductors of electricity. The reason they are not insulators, but semiconductors, is because with the proper application of heat or electrical pressure, electrons can be caused to break free of their bonds and move into the conduction band. Once in this band, they wander aimlessly through the crystal.

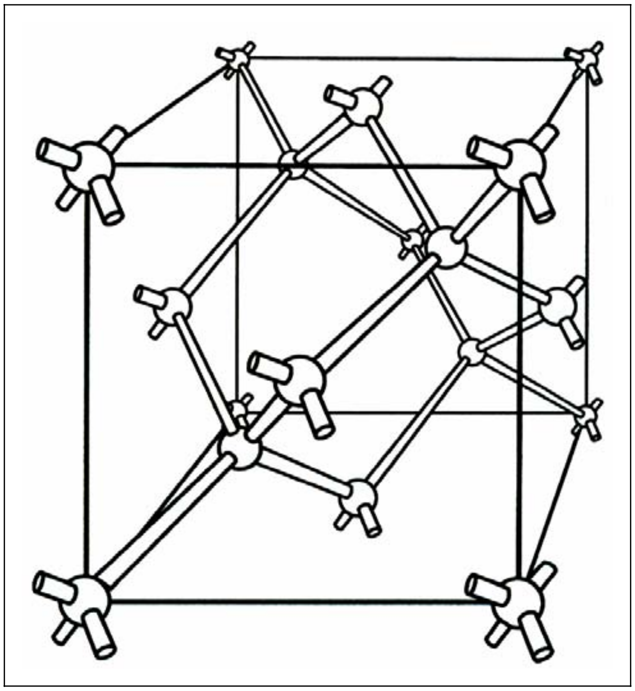


Figure 1-7. Typical Crystal Structure

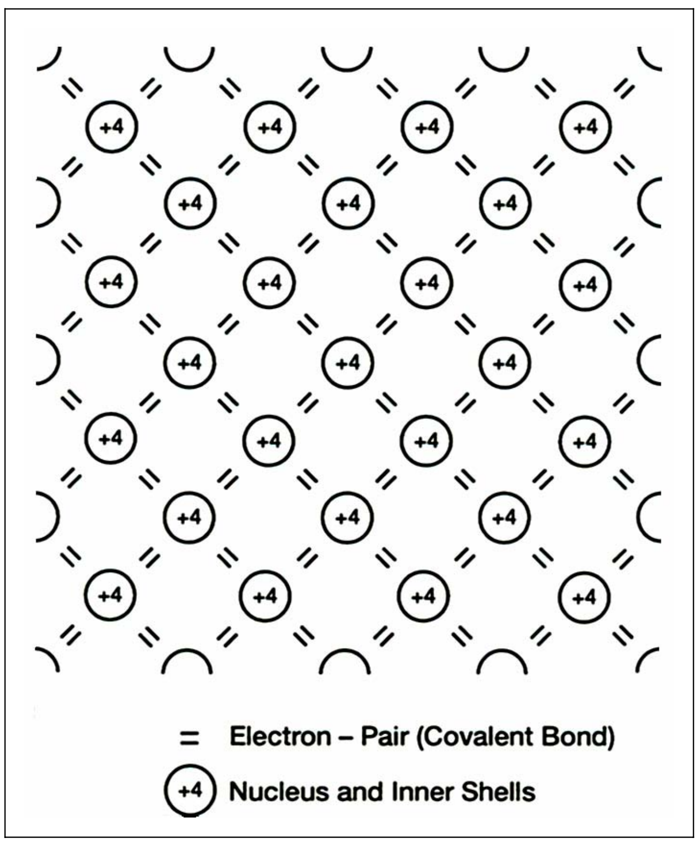


Figure 1-8. Two-Dimensional View of a Silicon Cubic Lattice

CONDUCTION PROCESS

1-48. As mentioned, energy can be added to electrons by applying heat. When enough energy is absorbed by the valence electrons, it is possible for them to break some of their covalent bonds. Once the bonds are broken, the electrons move to the conduction band where they are capable of supporting electric current. When a voltage is applied to a crystal containing these conduction band electrons, the electrons move through the crystal toward the applied voltage. This movement of electrons in a semiconductor is referred to as electron current flow.

1-49. There is still another type of current in a pure semiconductor. This current occurs when a covalent bond is broken and a vacancy is left in the atom by the missing valence electron. This vacancy is commonly referred to as a "hole." The hole is considered to have a positive charge because its atom is deficient by one electron that causes the protons to outnumber the electrons. As a result of this hole, a chain reaction begins when a nearby electron breaks its own covalent bond to fill the hole, leaving another hole. Then another electron breaks its bond to fill the previous hole, leaving still another hole. Each time an electron in this process fills a hole, it enters into a covalent bond. Even though an electron has moved from one covalent bond to another, the most important thing to remember is that the hole is also moving. Therefore, since this process of conduction resembles the movement of holes rather than electrons it is termed hole flow (short for hole current flow or conduction by holes). Hole flow is very similar to electron flow except that the holes move toward a negative potential and in an opposite direction to that of the electron. Since hole flow results from the breaking of covalent bonds, which are at the valence band level, then the electrons associated with this type of conduction contain only valence band energy and must remain in the valence band. However, the electrons associated with electron flow have conduction band energy and can therefore move throughout the crystal. A good analogy of hole flow is the movement of a hole through a tube filled with balls (see Figure 1-9).

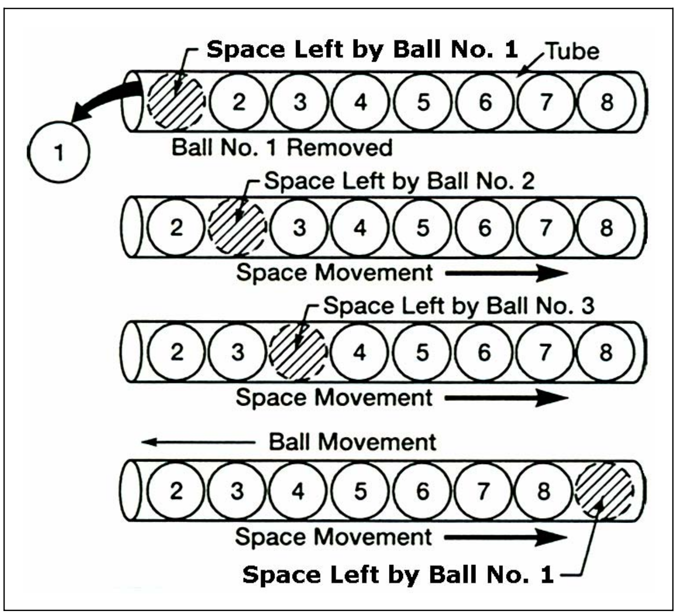


Figure 1-9. Analogy of Hole Flow

1-50. When ball number 1 is removed from the tube, a hole is left. This hole is then filled by ball number 2, which leaves still another hole. Ball number 3 then moves into the hole left by ball number 2. This causes still another hole to appear where ball 3 was. Notice the holes are moving to the right side of the tube. This action continues until all the balls have moved one space to the left in which time the hole moved eight spaces to the right and came to rest at the right-hand end of the tube.

1-51. In the theory just described, two-current carriers (the negative electron and the positive hole) were created by the breaking of covalent bonds. These carriers are referred to as electron-hole pairs. Since the semiconductor we have been covering contains no impurities, the number of holes in the electron-hole pairs is always equal to the number of conduction electrons. Another way of describing this condition where no impurities exist is by saying the semiconductor is INTRINSIC. The term intrinsic is also used to distinguish the pure semiconductor that we have been working with from one containing impurities.

DOPING PROCESS

1-52. The pure semiconductor already mentioned is basically neutral. It contains no free electrons in its conduction bands. Even with the application of thermal energy, only a few covalent bonds are broken, yielding a relatively small current flow. A much more efficient method of increasing current flow in semiconductors is by adding very small amounts of selected additives to them, generally no more than a few parts per million. These additives are called impurities and the process of adding them to crystals is referred to as DOPING. The purpose of semiconductor doping is to increase the number of free charges that can be moved by an external applied voltage. When an impurity increases the number of free electrons, the doped semiconductor is NEGATIVE or N-TYPE. The impurity that is added is known as an N-type impurity. However, an impurity that reduces the number of free electrons, causing more holes, creates a POSITIVE or P-TYPE semiconductor, and the impurity that was added to it is known as a P-type impurity. Semiconductors that are doped in this manner, either with N- or P-type impurities, are referred to as EXTRINSIC semiconductors.

N-Type Semiconductor

1-53. The N-type impurity easily loses its extra valence electron when added to a semiconductor material. This also increases the conductivity of the material by contributing a free electron. This type of impurity has five valence electrons and is called a PENTAVALENT impurity. Arsenic, antimony, bismuth, and phosphorous are pentavalent impurities. Since these materials give or donate one electron to the doped material, they are also called DONOR impurities.

1-54. When a pentavalent (donor) impurity, like arsenic, is added to germanium, it will form covalent bonds with the germanium atoms. Figure 1-10 shows an arsenic atom in a germanium lattice structure. Notice the arsenic atom in the center of the lattice. It has five valence electrons in its outer shell but uses only four of them to form covalent bonds with the germanium atoms, leaving one electron relatively free in the crystal structure. Pure germanium may be converted into a N-type semiconductor by “doping” it with any donor impurity having five valence electrons in its outer shell. Since this type of semiconductor (N-type) has a surplus of electrons, the electrons are considered MAJORITY carriers, while the holes, being few in number, are the MINORITY carriers.

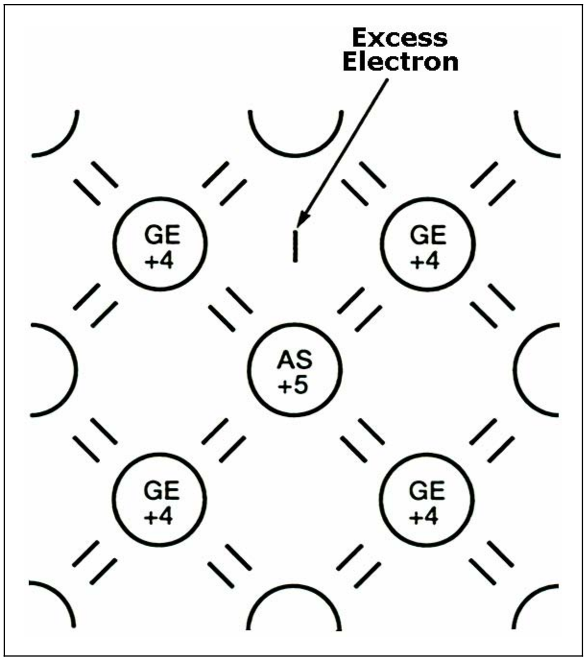


Figure 1-10. Germanium Crystal Doped With Arsenic

P-Type Semiconductor

1-55. The second type of impurity when added to a semiconductor material tends to compensate for its deficiency of one valence electron by acquiring an electron from its neighbor. Impurities of this type have only three valence electrons and are called TRIVALENT impurities. Aluminum, indium, gallium, and boron are trivalent impurities. Since these materials accept one electron from the doped material they are also called ACCEPTOR impurities.

1-56. A trivalent (acceptor) impurity element can also be used to dope germanium. In this case, the impurity is one electron short of the required amount of electrons needed to establish covalent bonds with four neighboring atoms. Therefore, in a single covalent bond there will be only one electron instead of two. This arrangement leaves a hole in that covalent bond. Figure 1-11 shows what happens when germanium is doped with an indium (I_N) atom. Notice, the indium atom in the figure is one electron short of the required amount of electrons needed to form covalent bonds with four neighboring atoms and therefore creates a hole in the structure. Gallium and boron, that are also trivalent impurities, exhibit these same characteristics when added to germanium. The holes can only be present in this type semiconductor when a trivalent impurity is used. Notice that a hole carrier is not created by the removal of an electron from a neutral atom. However, it is created when a trivalent impurity enters into covalent bonds with a tetravalent (four valence electrons) crystal structure. The holes in the type semiconductor (P-type) are considered the MAJORITY carriers since they are present in the material in the greatest quantity. The electrons, on the other hand, are the MINORITY carriers.

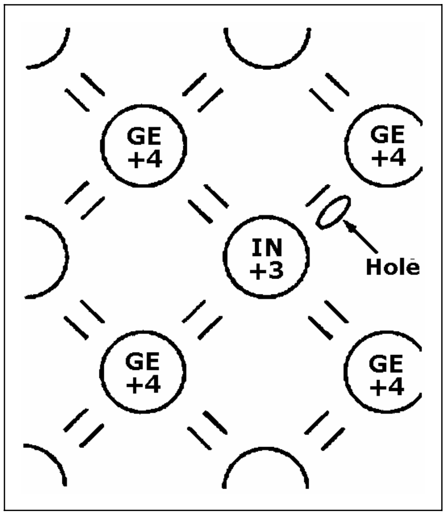


Figure 1-11. Germanium Crystal Doped With Indium

SEMICONDUCTOR DIODE

1-57. Joining a section of N-type semiconductor material with a similar section of P-type semiconductor material, will obtain a device known as a PN JUNCTION. The area where the N and P regions meet is appropriately called the junction. The unusual characteristic of this device makes it extremely useful in electronics as a diode rectifier. The diode rectifier or PN junction diode performs the same function as its counterpart in electron tubes but in a different way. The diode is nothing more than a two-element semiconductor device that makes use of the rectifying properties of a PN junction to convert AC into DC by permitting current flow in only one direction. Figure 1-12 shows the schematic symbol of a PN junction diode. The vertical bar represents the cathode (N-type material) since it is the source of electrons. The arrow represents the (P-type material) since it is the destination of the electrons. The label "CR1" is an alphanumerical code used to identify the diode. Figure 1-12 shows only one diode, so it is labeled CR1 (crystal rectifier number one). If there were four diodes shown, then the last diode would be labeled CR4. The heavy dark line shows electron flow (notice it is against the arrow). For further clarification, a pictorial view of a PN junction and an actual view of a semiconductor (one of many types) are also shown.

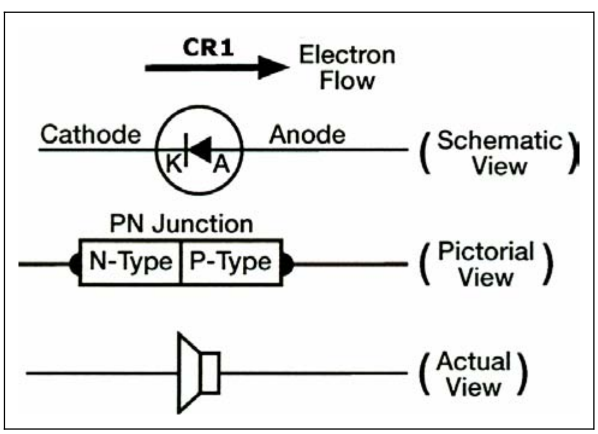


Figure 1-12. PN Junction Diode

CONSTRUCTION

1-58. Merely pressing together a section of P and N material is not sufficient to produce a rectifying junction. To form a proper PN junction, the semiconductor should be in one piece, but divided into a P-type impurity region and an N-type impurity region. This can be done in different ways. One way is to mix P-type and N-type impurities into a single crystal during the manufacturing process. Doing this causes a P-region to grow over part of a semiconductor's length and an N-region to grow over the other part. This is called a GROWN junction (see Figure 1-13, view (A)). Another way to produce a PN junction is to melt one type of impurity into a semiconductor of the opposite type impurity. For example, a pellet of acceptor impurity is placed on a wafer of N-type germanium and heated. Under controlled temperature conditions, the acceptor impurity fuses into the wafer to form a P-region within it (see Figure 1-13, view (B)). This type of junction is known as an ALLOY or FUSED-ALLOY junction. This is also one of the most commonly used junctions.

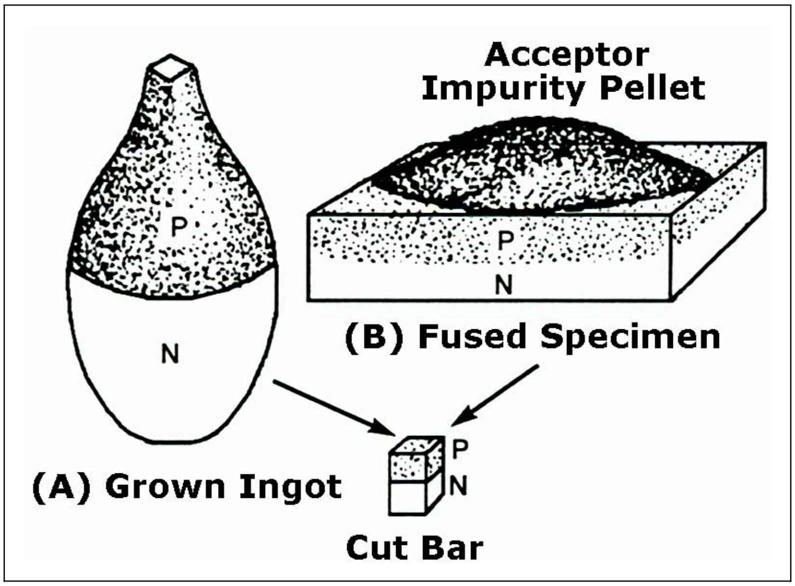


Figure 1-13. Grown and Fused PN Junctions From Which Bars are Cut

1-59. Figure 1-14 shows a POINT-CONTACT type of construction. It consists of a fine metal wire (called a cat whisker) that makes contact with a small area on the surface of a N-type semiconductor (view (A)). The PN union is formed in this process by quickly applying a high-surge current to the wire and the N-type semiconductor. The heat generated by this current converts the material nearest the point of contact to a P-type material (view (B)).

1-60. Still another process is to heat a section of semiconductor material to near melting and then diffuse impurity atoms into a surface layer. Regardless of the process, the object is to have a perfect bond everywhere along the union (interface) between the P and N materials. Proper contact along the union is important because the union (junction or interface) is the rectifying agent in the diode.

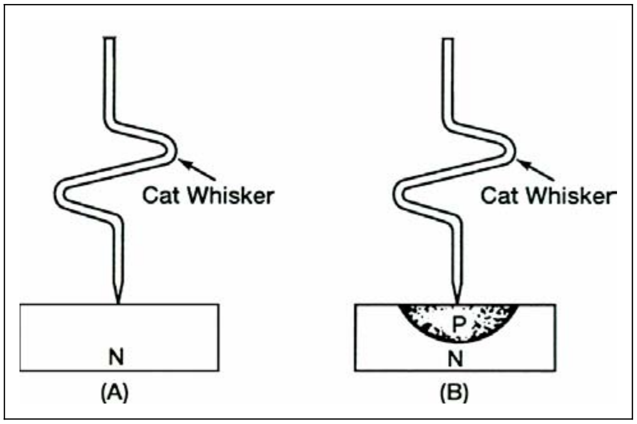


Figure 1-14. Point-Contact Type of Diode Construction

PN JUNCTION OPERATION

1-61. We should now be familiar with P- and N-type materials, how these materials are joined together to form a diode, and the function of the diode. However, before we can understand how the PN junction works, we must first consider current flow in the materials that make up the junction and then what happens initially within the junction when these two materials are joined together.

Current Flow in the N-Type Material

1-62. Figure 1-15 shows the current flow through the N-type material. Conduction in the N-type material of semiconductor, or crystal, is similar to conduction in a copper wire. That is, with voltage applied across the material, electrons will move through the crystal just as current would flow in a copper wire. The positive potential of the battery will attract the free electrons in the crystal. These electrons will leave the crystal and flow into the positive terminal of the battery. As an electron leaves the crystal, an electron from the negative terminal of the battery will enter the crystal, thereby completing the current path. Therefore, the majority current carriers in the N-type material (electrons) are repelled by the negative side of the battery and move through the crystal toward the positive side of the battery.

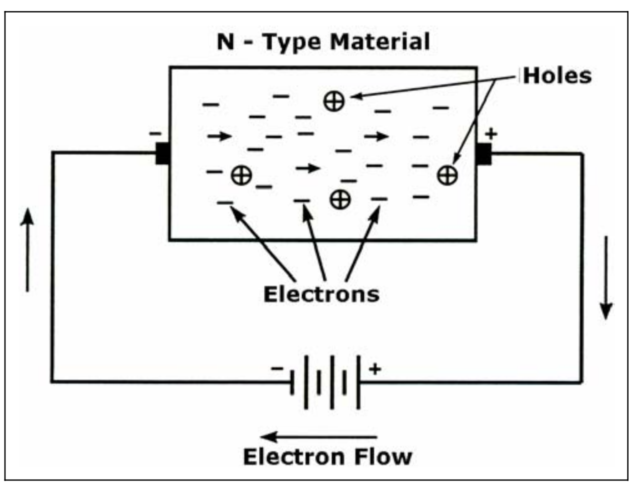


Figure 1-15. Current Flow in the N-Type Material

Current Flow in the P-Type Material

1-63. Figure 1-16 shows the current flow through the P-type material. Conduction in the P-type material is by positive holes, instead of negative electrons. The hole moves from the positive terminal of the P-type material to the negative terminal. Electrons from the external circuit enter the negative terminal of the material and fill holes in the vicinity of this terminal. At the positive terminal, electrons are removed from the covalent bonds, thereby creating new holes. This process continues as the steady stream of holes (hole current) moves toward the negative terminal.

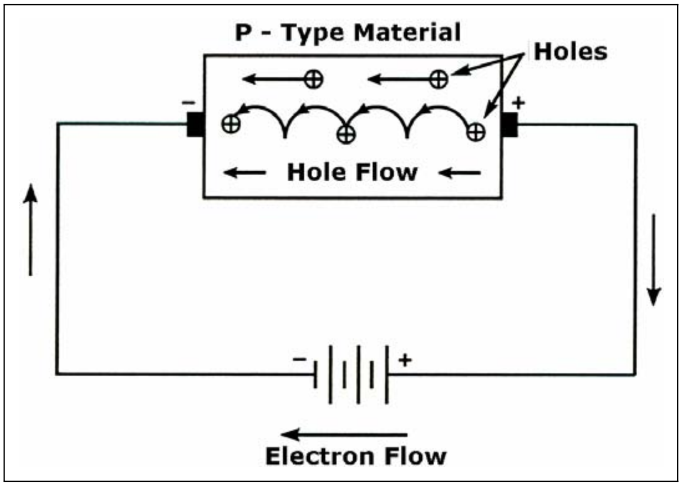


Figure 1-16. Current Flow in the P-Type Material

1-64. Notice in both N-type and P-type materials, current flow in the external circuit consists of electrons moving out of the negative terminal of the battery and into the positive terminal of the battery. Hole flow, on the other hand, only exists within the material itself.

Junction Barrier

1-65. Although the N-type material has an excess of free electrons, it is still electrically neutral. This is because the donor atoms in the N-type material were left with positive charges after free electrons became available by covalent bonding (the protons outnumbered the electrons). Therefore, for every free electron in the N-type material there is a corresponding positively charged atom to balance it. The end result is that the N-type material has an overall charge of zero.

1-66. By the same reasoning, the P-type material is also electrically neutral because the excess of holes in this material is exactly balanced by the number of electrons. Remember that the holes and electrons are still free to move in the material because they are only loosely bound to their parent atoms.

1-67. It seems that if we joined the N- and P-type materials together by one of the processes already mentioned, that all the holes and electrons would pair up. However, this does not happen. Instead the electrons in the N-type material diffuse (move or spread out) across the junction into the P-type material and fill some of the holes. At the same time the holes in the P-type material diffuse across the junction into the N-type material and are filled by N-type material electrons. This process is called JUNCTION RECOMBINATION and reduces the number of free electrons and holes in the vicinity of the junction. Since

there is a depletion, or lack of free electrons and holes in this area, it is known as the DEPLETION REGION.

1-68. The loss of an electron from the N-type material created a positive ion in the N-type material while the loss of a hole from the P-type material created a negative ion in the P-type material. These ions are fixed in place in the crystal lattice structure and cannot move. Therefore, they make up a layer of fixed charges on the two sides of the junction (see Figure 1-17). On the N side of the junction there is a layer of positively charged ions. On the P side of the junction there is a layer of negatively charged ions. An electrostatic field, represented by a small battery in the figure, is established across the junction between the oppositely charged ions. The diffusion of electrons and holes across the junction will continue until the magnitude of the electrostatic field is increased to the point where the electrons and holes no longer have enough energy to overcome it, and are repelled by the negative and positive ions respectively. At this point, equilibrium is established and for all practical purposes, the movement of carriers across the junction ceases. For this reason, the electrostatic field created by the positive and negative ions in the depletion region is called a barrier.

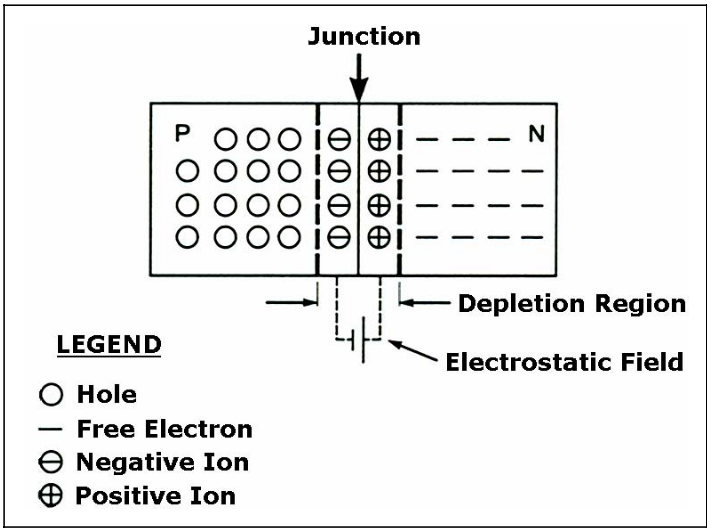


Figure 1-17. PN Junction Barrier Formation

1-69. The action just described occurs almost instantly when the junction is formed. Only the carriers in the immediate vicinity of the junction are affected. The carriers throughout the remainder of the N- and P-type materials are relatively undisturbed and remain in a balanced condition.

1-70. An external voltage applied to a PN junction is called BIAS. For example, if a battery is used to supply bias to a PN junction and is connected so that its voltage opposes the junction field, it will reduce the junction barrier and therefore aid current flow through the junction. This type of bias is known as FORWARD BIAS. Forward bias causes the junction to offer only minimum resistance to the flow of current.

1-71. Figure 1-18 shows forward bias. Notice the positive terminal of the bias battery is connected to the P-type material and the negative terminal of the battery is connected to the N-type material. The positive potential repels holes toward the junction where they neutralize some of the negative ions. At the same time, the negative potential repels electrons toward the junction where they neutralize some of the positive ions. Since ions on

both sides of the barrier are being neutralized, the width of the barrier decreases. So, the effect of the battery voltage in the forward bias direction is to reduce the barrier potential across the junction and to allow majority carriers to cross the junction. Current flow in the forward-biased PN junction is relatively simple. An electron leaves the negative terminal of the battery and moves to the terminal of the N-type material. It enters the N-type material, where it is the majority carrier, and moves to the edge of the junction barrier. Due to forward bias, the barrier offers less opposition to the electron and it will pass through the depletion region into the P-type material. The electron loses energy in overcoming the opposition of the junction barrier, and upon entering the P-type material, combines with a hole. The hole was produced when an electron was extracted from the P-type material by the positive potential of the battery. The created hole moves through the P-type material toward the junction where it combines with an electron.

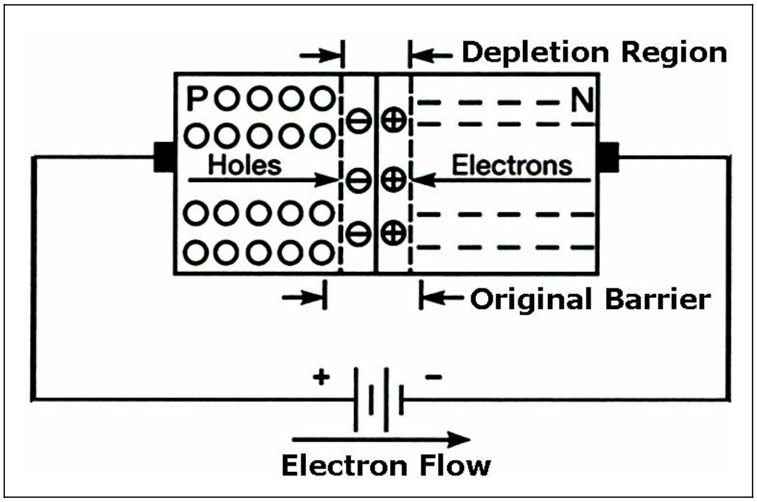


Figure 1-18. Forward-Biased PN Junction

1-72. It is important to remember that in the forward biased condition, conduction is by MAJORITY current carriers (holes in the P-type material and electrons in the N-type material). Increasing the battery voltage will increase the number of majority carriers arriving at the junction and will therefore increase the current flow. If the battery voltage is increased to the point where the barrier is greatly reduced, a heavy current will flow and the junction may be damaged from the resulting heat.

1-73. If the battery mentioned earlier is connected across the junction so that its voltage aids the junction, it will increase the junction barrier and thereby offer a high resistance to the current flow through the junction. This type of bias is known as REVERSE BIAS.

1-74. To reverse bias a junction diode, the negative battery terminal is connected to the P-type material and the positive battery terminal to the N-type material (see Figure 1-19). The negative potential attracts the holes away from the edge of the junction barrier on the P side, while the positive potential attracts the electrons away from the edge of the barrier on the N side. This action increases the barrier width because there are more negative ions on the P side of the junction and more positive ions on the N side of the junction. Notice in Figure 1-19 that the width of the barrier has increased. This increase in the number of ions prevents current flow across the junction by majority carriers. However, the current flow across the barrier is not quite zero because of the minority carriers crossing the junction. Remember, when the crystal is subjected to an external source of energy (such as light, heat, and so forth), electron-hole pairs are generated. The electron-hole pairs produce

minority current carriers. There are minority current carriers in both regions (holes in the N-type material and electrons in the P-type material). With reverse bias, the electrons in the P-type material are repelled toward the junction by the negative terminal of the battery. As the electrons move across the junction, it will neutralize a positive ion in the N-type material. Likewise, the holes in the N-type material will be repelled by the positive terminal of the battery toward the junction. As the hole crosses the junction, it will neutralize a negative ion in the P-type material. This movement of minority carriers is called MINORITY CURRENT FLOW, because the holes and electrons involved come from the electron-hole pairs that are generated in the crystal lattice structure, and not from the addition of impurity atoms.

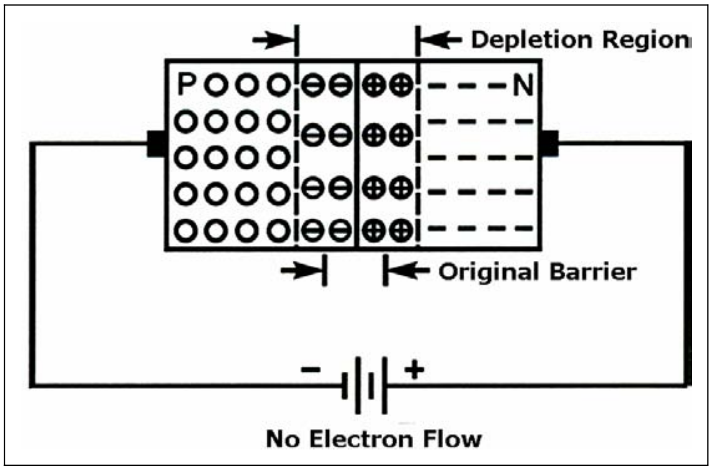


Figure 1-19. Reverse-Biased PN Junction

1-75. When a PN junction is reverse biased, there will be no current flow due to majority carriers but a very small amount of current due to minority carriers crossing the junction. However, at normal operating temperatures this small current may be neglected.

1-76. The most important point to remember about the PN junction diode is its ability to offer very little resistance to current flow in the forward-bias direction but maximum resistance to current flow when reverse biased. A good way to illustrate this point is by plotting a graph of the applied voltage versus the measured current. Figure 1-20 shows a plot of this vo1tage-current relationship (characteristic curve) for a typical PN junction diode.

1-77. We can use Ohm's law to determine the resistance from the curve (see Figure 1-20). Ohm's law is as follows:

$$R = \frac{E}{I}$$

For example at point A, the forward-bias voltage is 1 volt and the forward-bias current is 5 mA. This represents 200 ohms of resistance (1 volt/5 mA = 200 ohms). However, at point B, the voltage is 3 volts and the current is 50 milliamperes. This results in 60 ohms of resistance for the diode. Notice that when the forward-bias voltage was tripled (1 volt to 3 volts), the current increased ten times (5 mA to 50 mA). At the same time the forward-bias voltage increased, the resistance decreased from 200 ohms to 60 ohms. Therefore, when forward bias increases, the junction barrier gets smaller and its resistance to current flow decreases. However, the diode conducts very little when reverse

biased. Notice at point C, the reverse bias voltage is 80 volts and the current is only 100 microamperes. This results in 800k ohms of resistance, which is considerably larger than the resistance of the junction with forward bias. Because of these unusual features, the PN junction diode is often used to convert AC into DC (rectification).

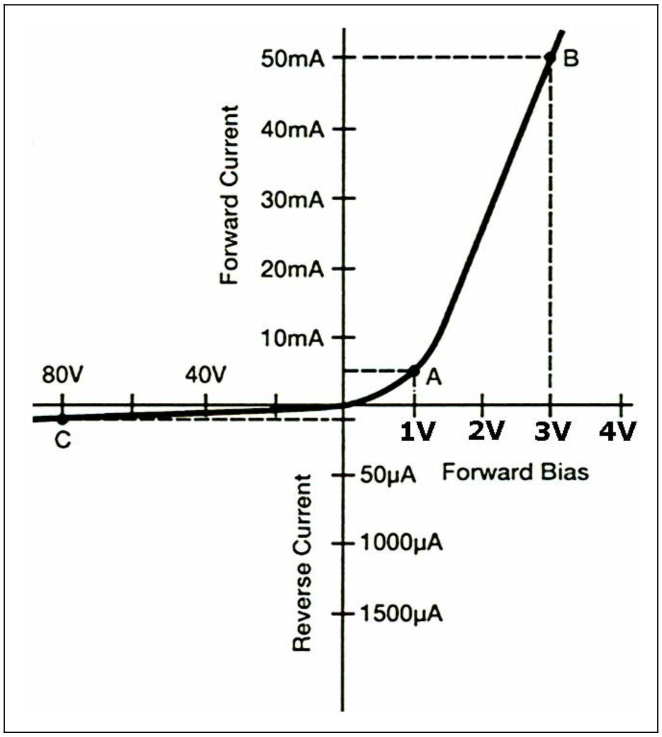


Figure 1-20. PN Junction Diode Characteristic Curve

PN JUNCTION APPLICATION

1-78. So far we have mentioned only rectification as one application for the diode. Variations in doping agents, semiconductor materials, and manufacturing techniques have made it possible to produce diodes that can be used in many different applications. Examples of these types of diodes are signal diodes, rectifying diodes, zener diodes (voltage protection diodes for power supplies), varactors (amplifying and switching diodes), and many more. Two of the most commonly used diodes are the signal diode and rectifier diode.

Half-Wave Rectifier

1-79. One of the most important uses of a diode is rectification. The normal PN junction diode is well suited for this purpose as it conducts very heavily when forward biased (low-resistance direction) and only slightly when reverse biased (high-resistance direction). If we place this diode in series with a source of AC power, then the diode will be forward and reverse biased every cycle. Since, in this situation, current flows more easily in one direction than the other, rectification is accomplished. The simplest rectifier circuit is a half-wave rectifier (see Figure 1-21) that consists of a diode, an AC power source, and a load resistor.

1-80. The transformer (T1) in Figure 1-21 provides the AC input to the circuit; the diode (CR1) provides the rectification; and the load resistor (R_L) serves the following two purposes:

- It limits the amount of current flow in the circuit to a safe level.
- It develops the output signal due to the current flow through it.

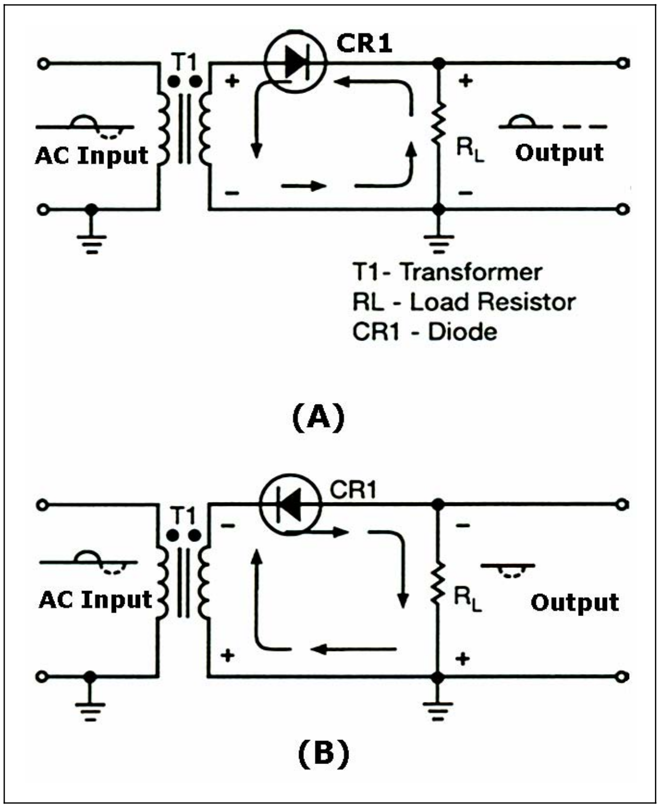


Figure 1-21. Simple Half-Wave Rectifier

1-81. Before describing how this circuit operates, you must know the definition of the word “load” as it applies to power supplies. Load is defined as any device that draws current. A device that draws little current is considered a light load while a device that draws a large amount of current is a heavy load. Remember that when we speak of “load,” we are speaking about the device that draws current from the power source. This device may be a simple resistor or one or more complicated electronic circuits.

1-82. During the positive half-cycle of the input signal (solid line) (see Figure 1-21, view (A)), the top of the transformer is positive with respect to ground. The dots on the transformer indicate points of the same polarity. With this condition, the diode is forward biased, the depletion region is narrow, the resistance of the diode is low, and current flows through the circuit in the direction of the solid lines. When this current flows through the load resistor, it develops a negative to positive voltage drop across it that appears as a positive voltage at the output terminal.

1-83. When the AC input goes in a negative direction, the top of the transformer becomes negative and the diode becomes reverse biased. With reverse bias applied to the diode, the depletion region increases, the resistance of the diode is high, and minimum

current flows through the diode. As indicated by the broken lines (see Figure 1-21), there is no output developed across the load resistor during the negative alternation of the input signal. Although only one cycle of input is shown, you should realize that the action described above continually repeats itself, as long as there is an input. Therefore, since only the positive half-cycles appear at the output, then this circuit converted the AC input into a positive pulsating DC voltage. The frequency of the output voltage is equal to the frequency of the applied AC signal since there is one pulse out for each cycle of the AC input. For example, if the AC input is 60 Hz then the input frequency would be 60 cycles per second and the output frequency would be 60 pulses per second.

1-84. However, if the diode were reversed (see Figure 1-21, view (B)), a negative output voltage would be obtained. This is because the current would be flowing from the top of R_L toward the bottom, making the output at the top of R_L negative in respect to the bottom or ground. Since current flows in this circuit only during half of the input cycle, it is called a half-wave rectifier.

1-85. The semiconductor diode shown in the figure can be replaced by a metallic rectifier and still achieve the same results. The metallic rectifier, sometimes referred to as a dry-disc rectifier, is a metal-to-semiconductor, large-area contact device. Its construction is distinctive; a semiconductor is sandwiched between two metal plates, or electrodes (see Figure 1-22). Notice that a barrier, with a resistance many times greater than that of the semiconductor material, is constructed on one of the metal electrodes. The contact having the barrier is a rectifying contact; the other contact is nonrectifying. Metallic rectifiers act just like the diodes previously covered in that they permit current to flow more readily in one direction than the other. However, the metallic rectifier is fairly large compared to the crystal diode shown in Figure 1-23. The reasons for this is that metallic rectifier units are stacked (to prevent inverse voltage breakdown), have large area plates (to handle high currents), and usually have cooling fins (to prevent overheating).

1-86. There are many known metal-semiconductor combinations that can be used for contact rectification. Copper oxide and selenium devices are by far the most popular. Copper oxide and selenium are often used over other types of metallic rectifiers because they have a large forward current per unit contact area, low forward voltage drop, good stability, and a lower aging rate. In practical applications, the selenium rectifier is used where a relatively large amount of power is required. However, copper-oxide rectifiers are generally used in small-current applications such as AC meter movements or for delivering DC to circuits requiring not more than 10 amperes.

1-87. Since metallic rectifiers are affected by temperature, atmospheric conditions, and aging (in the case of copper oxide and selenium), they are being replaced by the improved silicon crystal rectifier. The silicon rectifier replaces the bulky selenium rectifier as to current and voltage rating and can operate at higher ambient (surrounding) temperatures.

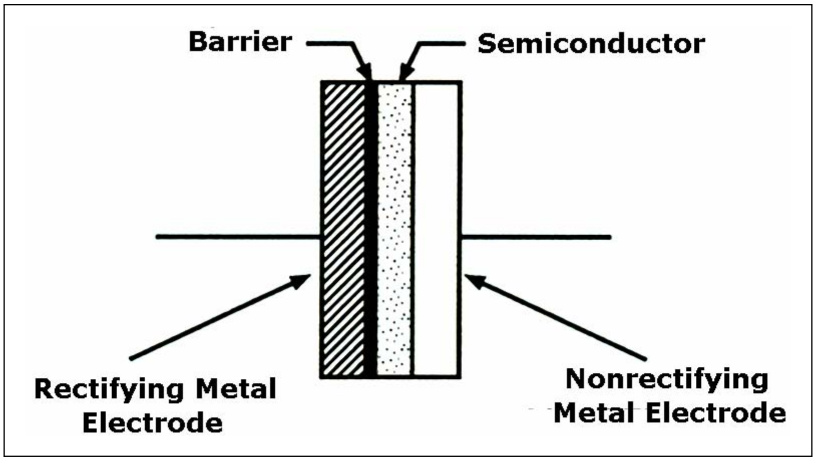


Figure 1-22. Metallic Rectifier

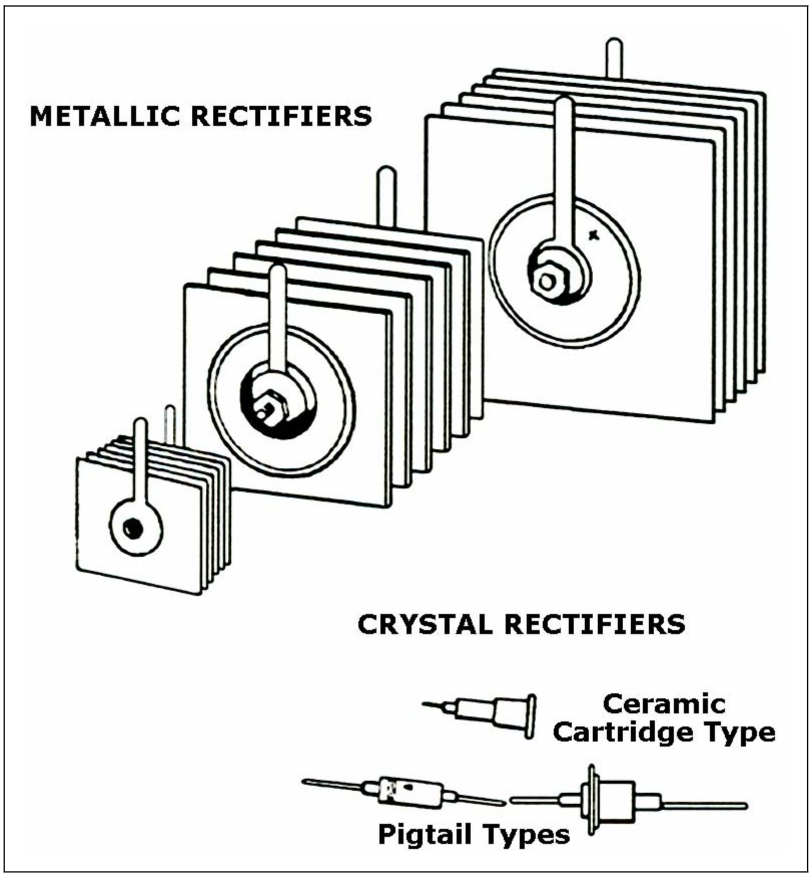


Figure 1-23. Different Types of Crystal and Metallic Rectifiers

Diode Switch

1-88. In addition to their use as simple rectifiers, diodes are also used in circuits that mix signals together (mixers), detect the presence of a signal (detector), and act as a switch "to open or close a circuit." Diodes used in these applications are commonly referred to as "signal diodes." The simplest application of a signal diode is the basic diode switch (see Figure 1-24).

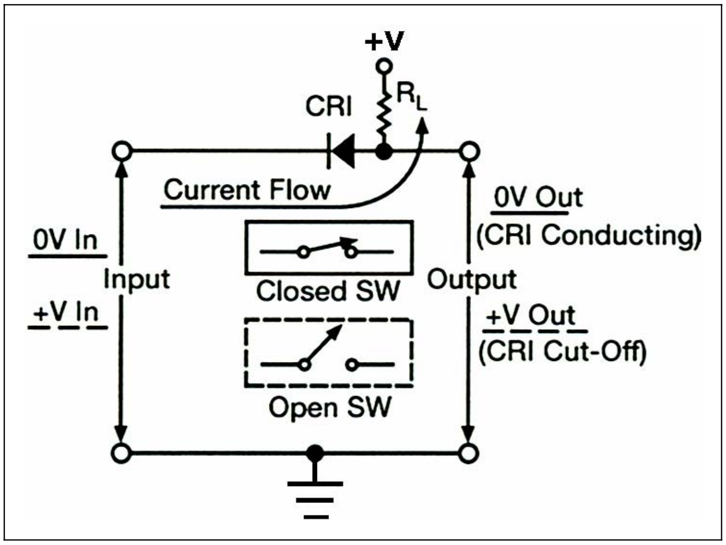


Figure 1-24. Basic Diode Switch

1-89. When the input to this circuit is at zero potential, the diode is forward biased because of the zero potential on the cathode and the positive voltage on the anode. In this condition, the diode conducts and acts as a straight piece of wire because of its very low forward resistance. In effect, the input is directly coupled to the output resulting in zero volts across the output terminals. Therefore, the diode acts as a closed switch when its anode is positive with respect to its cathode.

1-90. Applying a positive input voltage (equal to or greater than the positive voltage supplied to the anode) to the diode's cathode, the diode will be reverse biased. In this situation, the diode is cut off and acts as an open switch between the input and output terminals. So, with no current flow in the circuit, the positive voltage on the diode's anode will be felt at the output terminal. Therefore, the diode acts as an open switch when it is reverse biased.

DIODE CHARACTERISTICS

1-91. Semiconductor diodes have properties that enable them to perform many different electronic functions. Engineers and technicians, in order to do their job, must be supplied with data on these different types of diodes. The information presented for this purpose is called DIODE CHARACTERISTICS. Manufacturers supply these characteristics either in their manuals or on specification sheets (data sheets). Since there are many manufacturers and diode types, it is not practical to show you a specification sheet and call it typical. Aside from the differences between manufacturers, a single manufacturer may even supply specification sheets that differ both in format and content. Despite these differences, certain performance and design information is normally required.

1-92. A standard specification sheet usually has a brief description of the diode. Included in this description is the type of diode, the major area of application, and any special features. Of particular interest is the specific application for which the diode is suited. The manufacturer also provides a drawing of the diode that gives dimensions, weight, and, if appropriate, any ID marks. In addition to the above data, the following information is also provided:

- A static operating table (giving spot values of parameters under fixed conditions).
- A characteristic curve similar to the one in Figure 1-20 (showing how parameters vary over the full operating range).
- Diode ratings (which are the limiting values of operating conditions outside which could cause diode damage).

1-93. Manufacturers specify these various diode operating parameters and characteristics with “letter symbols” in accordance with fixed definitions. Table 1-1 is a list, by letter symbol, of the major electrical characteristics for rectifier and signal diodes.

NOTE: The electrical characteristics (by letter symbols) for the other types of diodes will be covered later.

Table 1-1. Major Electrical Characteristics for Rectifier and Signal Diodes

RECTIFIER DIODES
▪ **DC BLOCKING VOLTAGE [V_R]** - the maximum reverse DC voltage that will not cause breakdown.
▪ **AVERAGE FORWARD VOLTAGE DROP [V_F (A_V)]** - the average forward voltage drop across the rectifier given at a specified forward current and temperature.
▪ **AVERAGE RECTIFIER FORWARD CURRENT [I_F (A_V)]** - the average rectified forward current at a specified temperature, usually at 60 Hz with a resistive load.
▪ **AVERAGE REVERSE CURRENT [I_R (A_V)]** - the average reverse current at a specified temperature, usually at 60 Hz.
▪ **PEAK SURGE CURRENT [I_{SURGE}]** - the peak current specified for a given number of cycles or portion of a cycle.

Table 1-1. Major Electrical Characteristics for Rectifier and Signal Diodes (continued)

SIGNAL DIODES
▪ **PEAK REVERSE VOLTAGE [PRV]** - the maximum reverse voltage that can be applied before reaching the breakdown point. PRV also applies to the rectifier diode.
▪ **REVERSE CURRENT [I_R]** - the small value of DC that flows when a semiconductor diode has reverse bias.
▪ **MAXIMUM FORWARD VOLTAGE DROP AT INDICATED FORWARD CURRENT [V_F@I_F] -** the maximum forward voltage drop across the diode at the indicated forward current.
▪ **REVERSE RECOVERY TIME (T_{RR}) -** the maximum time taken for the forward bias diode to recover its reverse bias.

1-94. The ratings of a diode (as stated earlier) are the limiting values of operating conditions which if exceeded could cause damage to a diode by either voltage breakdown or overheating. The PN junction diodes are generally rated for MAXIMUM AVERAGE FORWARD CURRENT, PEAK RECURRENT FORWARD CURRENT, MAXIMUM SURGE CURRENT, and PEAK REVERSE VOLTAGE.

- Maximum average forward current is usually given at a specified temperature, usually 25º C (77º F) and refers to the maximum amount of average current that can be permitted to flow in the forward direction. If this rating is exceeded, structure breakdown can occur.
- Peak recurrent forward current is the maximum peak current which can be permitted to flow in the forward direction in the form of recurring pulses.
- Maximum surge current is the maximum current permitted to flow in the forward direction in the form of non-recurring pulses. Current should not equal this value for more than a few milliseconds.
- Peak reverse voltage is one of the most important ratings. PRV indicates the maximum reverse-bias voltage that may be applied to a diode without causing junction breakdown.

All of the above ratings are subject to change with temperature variations. For example, if the operating temperature is above that stated for the ratings, then the ratings must be decreased.

DIODE IDENTIFICATION

1-95. Many types of diodes vary in size. Diodes can be the size of a pinhead (used in subminiature circuitry) to large 250-ampere diodes (used in high power circuits). Since there are so many different types of diodes, then some system of ID is needed to distinguish one diode from another. This is accomplished with the semiconductor identification system (see Figure 1-25). This system is not only used for diodes but also for transistors and many other special semiconductor devices. The identification system uses numbers and letters to establish a code in order to identify different types of semiconductor devices. The first number in the code indicates the number of junctions in the semiconductor device and is a number, one less than the number of active elements.

Therefore, 1 designates a diode; 2 designates a transistor (which may be considered as made up of two diodes); and 3 designates a tetrode (a four-element transistor). The letter “N” following the first number indicates a semiconductor. The 2- or 3-digit number following the letter “N” is a serialized ID number. If needed, this number may contain a suffix letter after the last digit. For example, the suffix letter “M” may be used to describe matching pairs of separate semiconductor devices or the letter “R” may be used to indicate reverse polarity. Other letters are used to indicate modified versions of the device that can be substituted for the basic numbered unit. For example, a semiconductor diode designated as type 1N345A signifies a two-element diode (1) of semiconductor material (N) that is an improved version (A) of type 345.

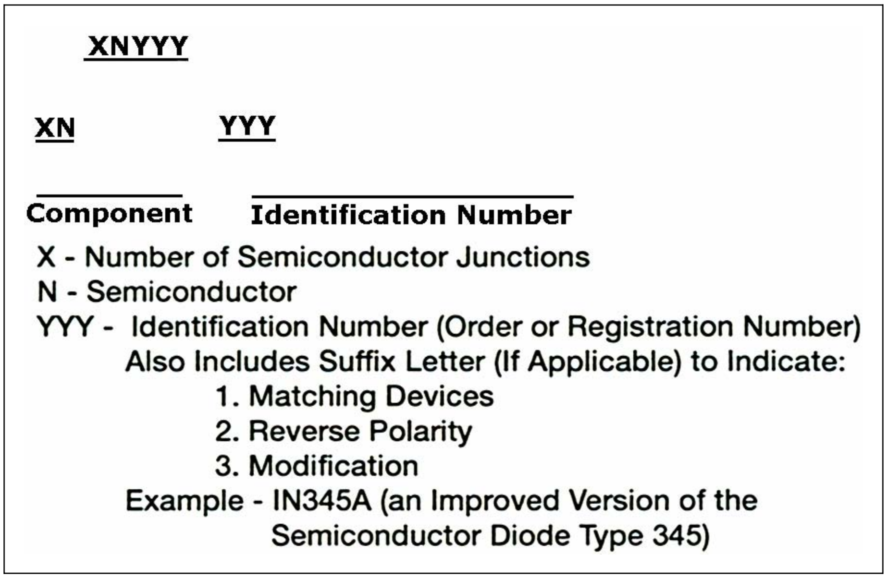


Figure 1-25. Semiconductor Identification System

1-96. When working with different types of diodes, it is also necessary to distinguish one end of the diode from the other (anode from cathode). To do this, manufacturers generally code the cathode end of the diode with a “k”, “+”, “cath”, “color dot or band”, or by an unusual shape (raised edge or taper) (see Figure 1-26). Sometimes, standard color code bands are placed on the cathode end of the diode. This serves two purposes:

- To identify the cathode end of the diode.
- To identify the diode by number.

1-97. Figure 1-27 shows the standard diode color code system. The ID number for a diode with a brown, orange, and white band at one terminal (with brown being a “1”, orange a “3”, and white “9”), would be identified as a type 139 semiconductor diode, or specifically 1N139. Remember, whether the diode is a small crystal type or a large power rectifier type; both are still represented schematically by the schematic symbol as shown in Figure 1-12.

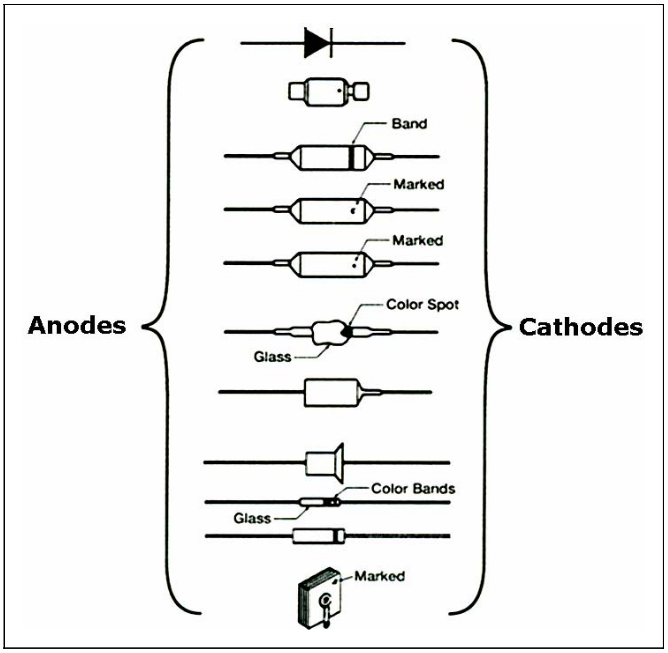
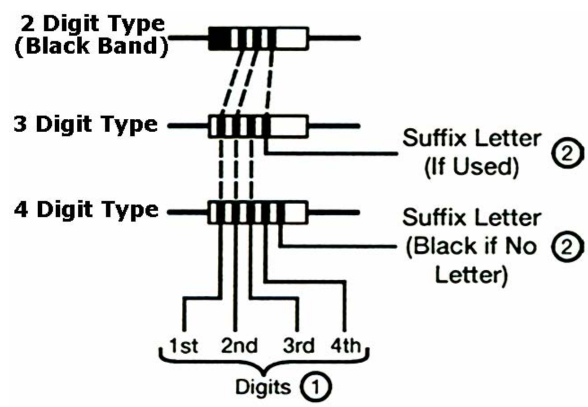


Figure 1-26. Semiconductor Diode Markings



Color	① Digit	② Diode Suffix Letter
Black	0	-
Brown	1	A
Red	2	B
Orange	3	C
Yellow	4	D
Green	5	E
Blue	6	F
Violet	7	G
Gray	8	H
White	9	J
Silver	-	-
Gold	-	-
None	-	-

Figure 1-27. Semiconductor Diode Color Code System

DIODE MAINTENANCE

1-98. Diodes are rugged and efficient. They are also expected to be relatively trouble free. Protective encapsulation processes and special coating techniques have even further increased their life expectancies. In theory, a diode should last indefinitely. However, if diodes are subjected to current overloads, their junctions will be damaged or even destroyed. The application of excessively high operating voltages can also damage or destroy junctions through arc-over or excessive reverse currents. One of the greatest dangers to the diode is heat. Heat causes more electron-hole pairs to be generated, which in turn increases current flow. This increase in current generates more heat and the cycle repeats itself until the diode draws excessive current. This action is referred to as THERMAL RUNAWAY and eventually causes diode destruction. Use extreme caution when working with equipment containing diodes to ensure that these problems do not occur and cause irreparable diode damage.

1-99. There are a number of ways to prevent diode damage. Observe the following special safety precautions when working with diodes.

PRECAUTIONS

- Never remove or insert a diode into a circuit with voltage applied.
- Never pry diodes to loosen them from their circuits.
- Always be careful when soldering to ensure that excessive heat is not applied to the diode.
- When testing a diode, ensure that the test voltage does not exceed the diode's maximum allowable voltage.
- Never put your fingers across a signal diode because the static charge from your body could short it out.
- Always replace a diode with one of the same type or with a direct replacement.
- Ensure a replacement diode is put into a circuit in the correct direction.

1-100. You can check a diode in a number of ways if it has been subjected to excessive voltage or temperature and is suspected of being defective. The most convenient and quickest way of testing a diode is with an ohmmeter (see Figure 1-28). To make this check, simply disconnect one of the diode leads from the circuit wiring and make resistance measurements across the leads of the diode. The resistance measurements obtained depend upon the test-lead polarity of the ohmmeter; therefore, two measurements must be taken. The first measurement is taken with the test leads connected to either end of the diode and the second measurement is taken with the test leads reversed on the diode. The larger resistance value is assumed to be the reverse (back) resistance of the diode and the smaller resistance (front) value is assumed to be the forward resistance. Measurements can be made for comparison purposes using another identical-type diode, known to be good, as a standard. Two high-value resistance measurements indicate that the diode is open or has a high forward resistance; two low-value resistance measurements indicate that the diode is shorted or has a low reverse resistance. A normal set of measurements will show a high resistance in the reverse direction and a low resistance in the forward direction. The diode's efficiency is determined by how low the forward resistance is as compared with the reverse resistance. Therefore, it is desirable to have as great a ratio (often known as the front to back ratio or the back to front ratio) as possible between the reverse and forward resistance

measurements. However, as a rule of thumb, a small signal diode will have a ratio of several hundred to one, while a power rectifier can operate satisfactorily with a ratio of 10 to 1.

1-101. Remember that the ohmmeter check is NOT conclusive. It is still possible for a diode to check well under this test. However, it can still breakdown when replaced in the circuit. The problem is that the meter used to check the diode uses a lower voltage than the diode usually operates at in the circuit.

1-102. Another thing to remember is that a diode should not be condemned because two ohmmeters give different readings. This occurs due to the different internal resistance of the ohmmeters and the different states of charge on the ohmmeter batteries. Since each ohmmeter sends a different current through the diode, the two resistance values read on the meters will not be the same.

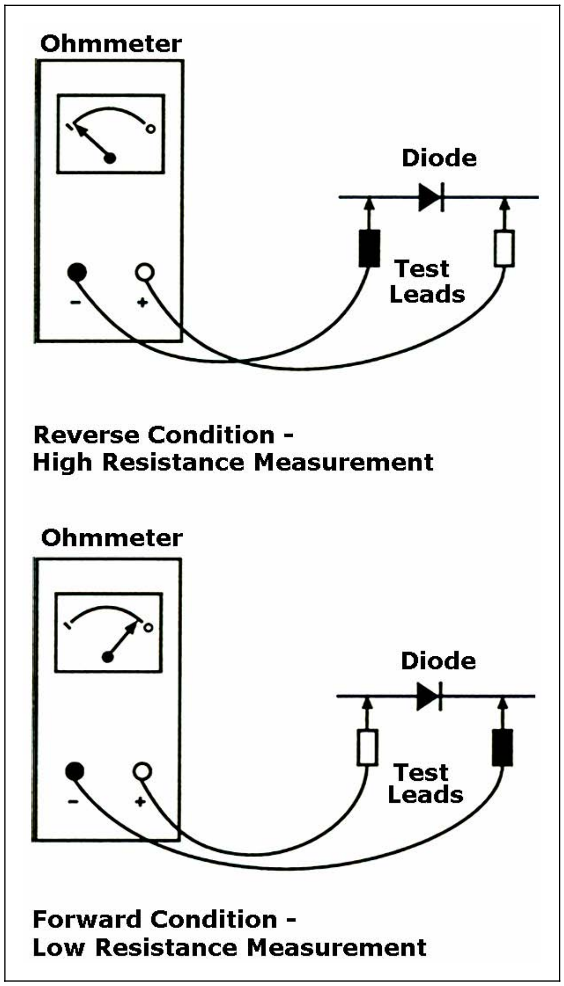


Figure 1-28. Checking a Diode With an Ohmmeter

1-103. Another way of checking a diode is with the substitution method. In this method, a good diode is substituted for a questionable diode. Use this technique only after you have made voltage and resistance measurements to make sure that there is no circuit defect that might damage the substitution diode. If more than one defective diode is present in the equipment section, where trouble has been localized, this method becomes cumbersome,

since several diodes may have to be replaced before the trouble is corrected. To determine which stages failed and which diodes are not defective, all of the removed diodes must be tested. You can do this by observing whether the equipment operates correctly as each of the removed diodes is reinserted into the equipment.

1-104. The only valid check of a diode is a dynamic electrical test that determines the diode's forward current (resistance) and reverse current (resistance) parameters. You can do this test by using various crystal diode test sets that are readily available from many manufacturers.

SUMMARY

1-105. Now that we have completed this chapter, the following is a short review of the more important points. Answer the check-on-learning questions, found after the summary, to determine how much you have learned from this chapter.

***THE UNIVERSE* -** consists of two main parts (matter and energy).

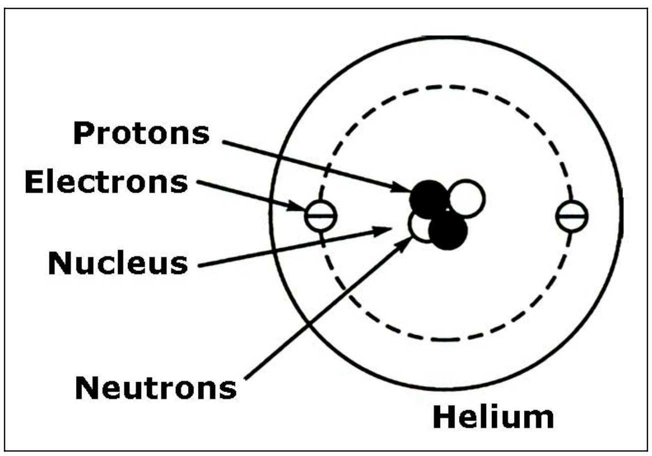
***MATTER* -** anything that occupies space and has weight. Rocks, water, and air are examples of matter. Matter may be found in any one of three states: solid, liquid, and gaseous. It can also be composed of either an element or a combination of elements.

***ELEMENT* -** a substance that cannot be reduced to a simpler form by chemical means. Iron, gold, silver, copper, and oxygen are all good examples of elements.

***COMPOUND* -** a chemical combination of two or more elements. Water, table salt, ethyl alcohol, and ammonia are all examples of compounds.

***MOLECULE* -** the smallest part of a compound that has all the characteristics of the compound. Each molecule contains some of the atoms of each of the elements forming the compound.

***ATOM* -** the smallest particles into which an element can be broken down and still retain all its original properties. An atom is made up of electrons, protons, and neutrons. The number and arrangement of these particles determine the kind of element.



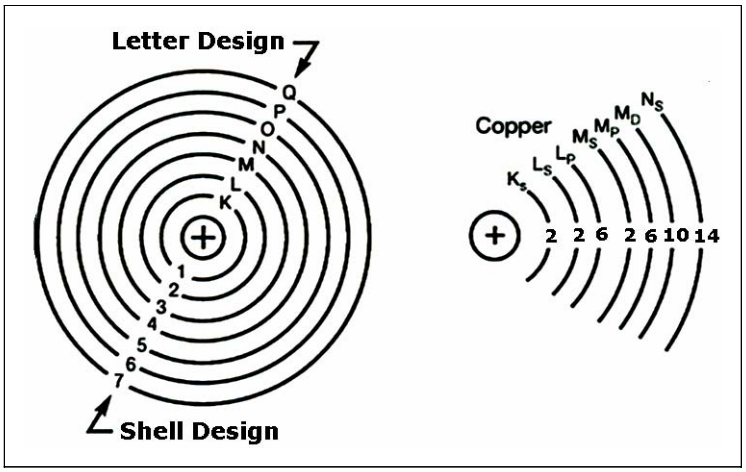
***ELECTRON* -** a small negative charge of electricity.

PROTON **-** a positive charge of electricity that is equal and opposite to the charge of the electron. However, the mass of the proton is approximately 1,837 times that of the electron.

NEUTRON **-** a neutral particle in that it has no electrical charge. The mass of the neutron is approximately equal to that of the proton.

ELECTRON'S ENERGY LEVEL **-** the amount of energy required by an electron to stay in orbit. Just by the electron's motion alone, it has kinetic energy. The electron's position in reference to the nucleus gives it potential energy. An energy balance keeps the electron in orbit and as it gains or loses energy, it assumes an orbit further or closer to the center of the atom.

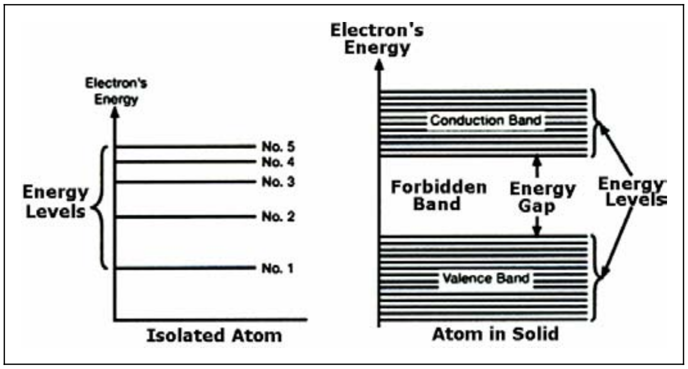
SHELLS AND SUBSHELLS **-** the orbits of the electrons in an atom. Each shell can contain a maximum number of electrons that can be determined by the formula $2N^2$. Shells are lettered K through Q (starting with K, which is the closest to the nucleus). The shell can also be split into four subshells labeled s, p, d, and f, which can contain 2, 6, 10, and 14 electrons, respectively.



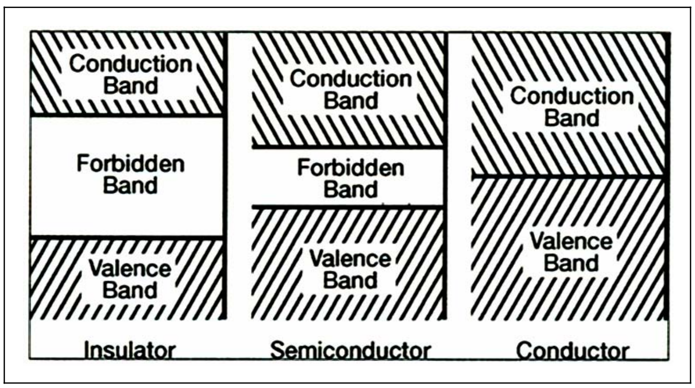
VALENCE **-** the ability of an atom to combine with other atoms. The valence of an atom is determined by the number of electrons in the atom's outermost shell. This shell is referred to as the VALENCE SHELL. The electrons in the outermost shell are called VALENCE ELECTRONS.

IONIZATION **-** the process by which an atom loses or gains electrons. An atom that loses some of its electrons in this process becomes positively charged and is called a POSITIVE ION. An atom that has an excess number of electrons is negatively charged and is called a NEGATIVE ION.

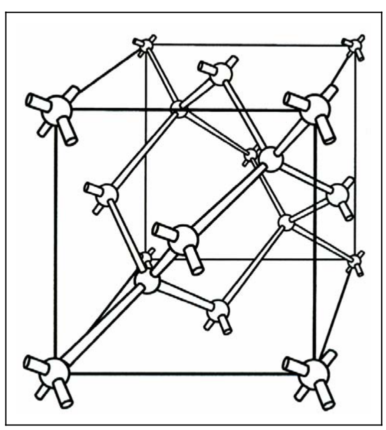
***ENERGY BANDS* -** groups of energy levels that result from the close proximity of atoms in a solid. The three most important energy bands are the CONDUCTION BAND, FORBIDDEN BAND, and VALENCE BAND.



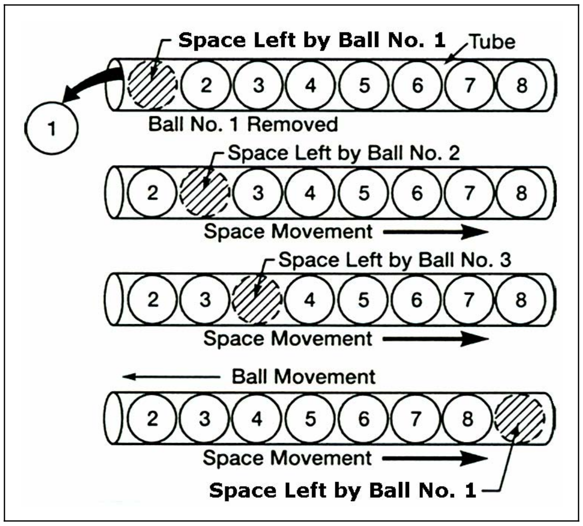
CONDUCTORS, SEMICONDUCTORS, AND INSULATORS – these are categorized by using the energy band concept. It is the width of the forbidden band which determines whether a material is an insulator, a semiconductor, or a conductor. A CONDUCTOR has a very narrow forbidden band or none at all. A SEMICONDUCTOR has a medium width forbidden band. An INSULATOR has a wide forbidden band.



***COVALENT BONDING* -** the sharing of valence electrons between two or more atoms. It is this bonding that holds the atoms together in an orderly structure called a CRYSTAL.

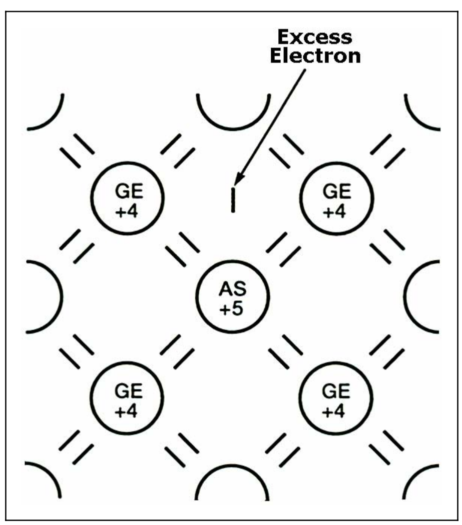


CONDUCTION PROCESS IN A SEMICONDUCTOR - accomplished by two different types of current flow (HOLE FLOW and ELECTRON FLOW). Hole flow is very similar to electron flow except that holes (positive charges) move toward a negative potential and in an opposite direction to that of the electrons. In an INTRINSIC semiconductor (one which does not contain any impurities), the number of holes always equals the number of conducting electrons.



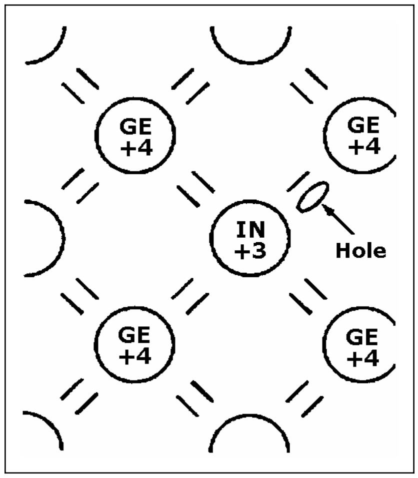
DOPING - the process by which small amounts of selected additives, called impurities, are added to semiconductors to increase their current flow. Semiconductors that undergo this treatment are referred to as EXTRINSIC SEMICONDUCTORS.

N-TYPE SEMICONDUCTOR - one that is doped with an N-type or donor impurity (an impurity that easily loses its extra electron to the semiconductor causing it to have an excess number of free electrons). Since this type of semiconductor has a surplus of electrons, the electrons are considered the majority current carriers while the holes are the minority current carriers.

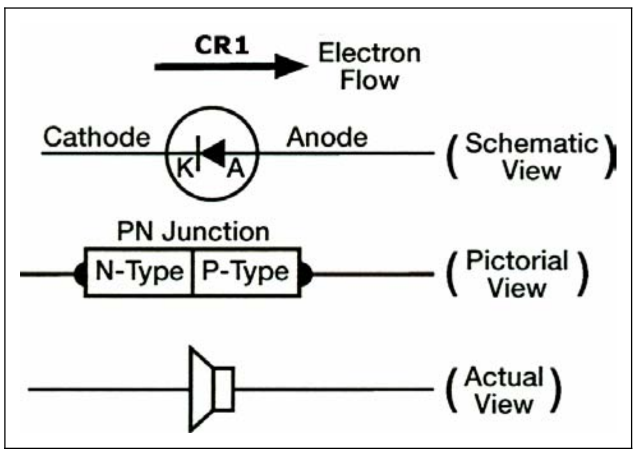


P-TYPE SEMICONDUCTOR - one that is doped with a P-type or acceptor impurity (an impurity that reduces the number of free electrons causing more

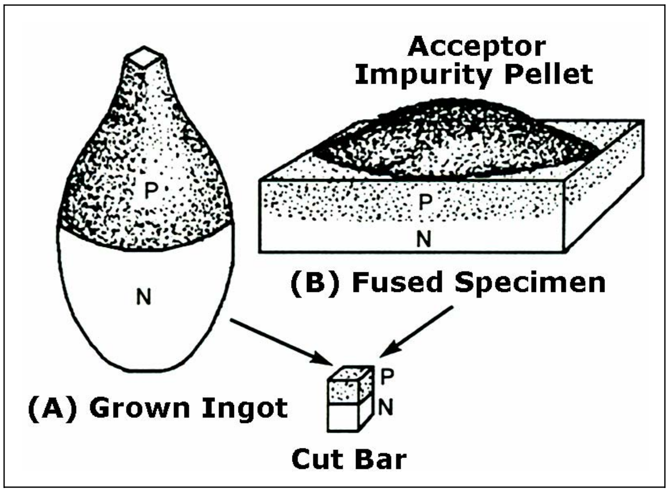
holes). The holes in this type semiconductor are the majority current carriers since they are present in the greatest quantity while the electrons are the minority current carriers.



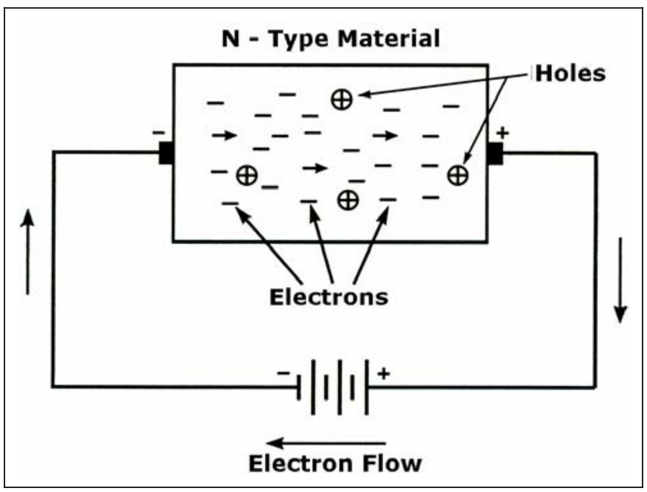
SEMICONDUCTOR DIODE **-** also known as a PN JUNCTION DIODE, is a two-element semiconductor device that makes use of the rectifying properties of a PN junction to convert AC into DC by permitting current flow in only one direction.



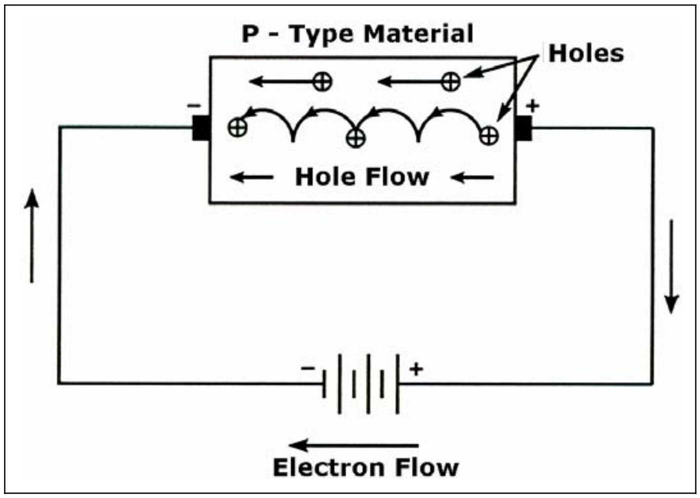
PN JUNCTION CONSTRUCTION - varies from one manufacturer to the next. Some of the more commonly used manufacturing techniques are GROWN, ALLOY or FUSED-ALLOY, DIFFUSED, and POINT-CONTACT.



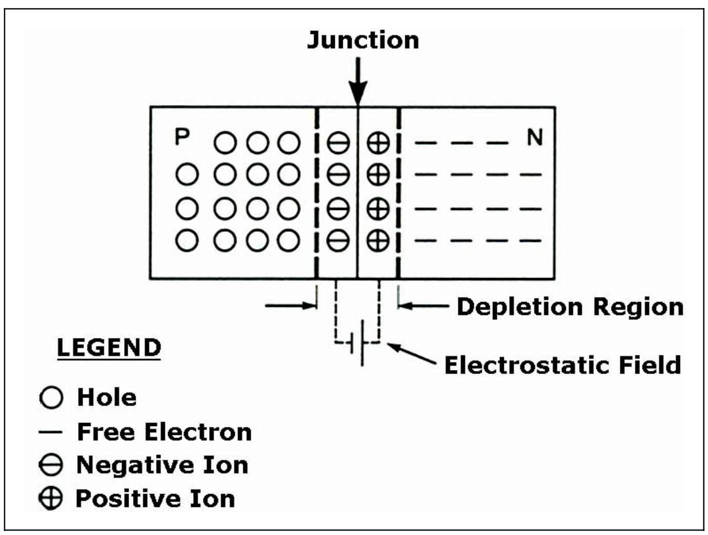
CURRENT FLOW IN AN N-TYPE MATERIAL – this is similar to conduction in a copper wire. That is, with voltage applied across the material, electrons will move through the crystal toward the positive terminal just like current flows in a copper wire.



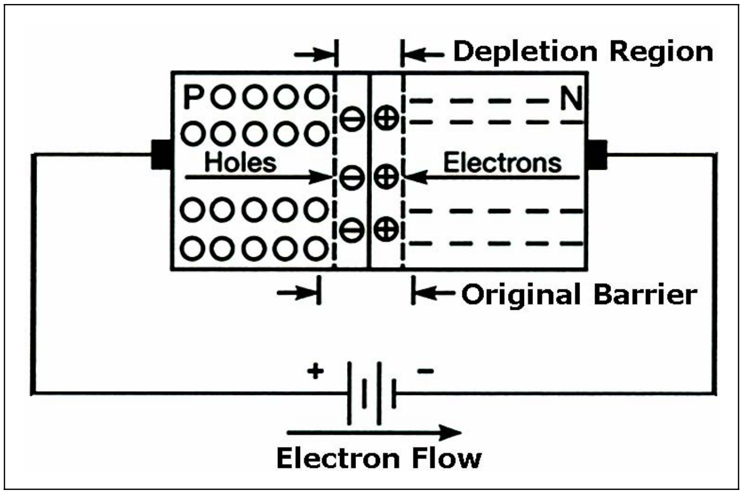
CURRENT FLOW IN A P-TYPE MATERIAL – conduction is by positive holes instead of negative electrons. Unlike the electron, the hole moves from the positive terminal of the P-type material to the negative terminal.



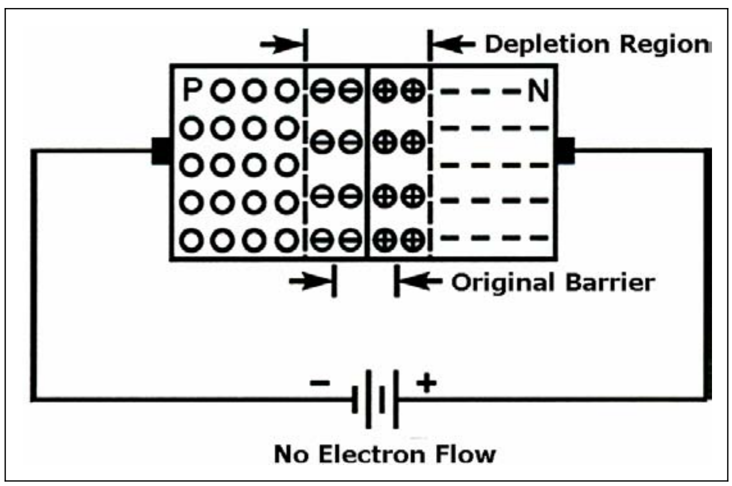
JUNCTION BARRIER **-** an electrostatic field that has been created by the joining of a section of N-type material with a section of P-type material. Since holes and electrons must overcome this field to cross the junction, the electrostatic field is commonly called a BARRIER. Since there is a lack or depletion of free electrons and holes in the area around the barrier, this area has become known as the DEPLETION REGION.



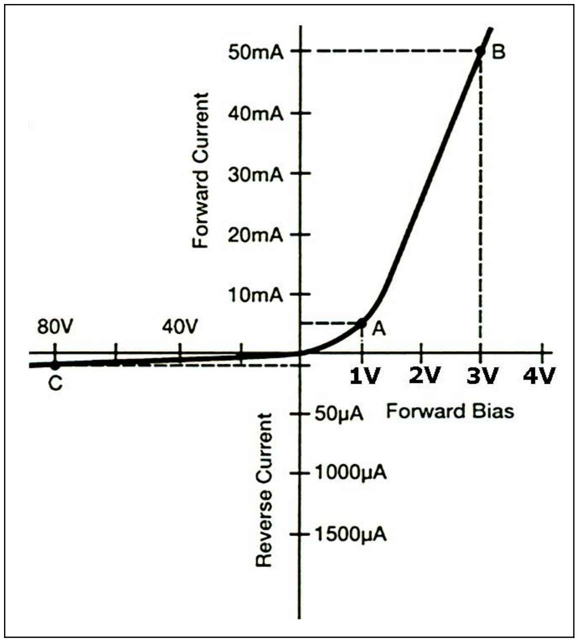
FORWARD BIAS - an external voltage that is applied to a PN junction to reduce its barrier and therefore aid current flow through the junction. To accomplish this function, the external voltage is connected so that it opposes the electrostatic field of the junction.



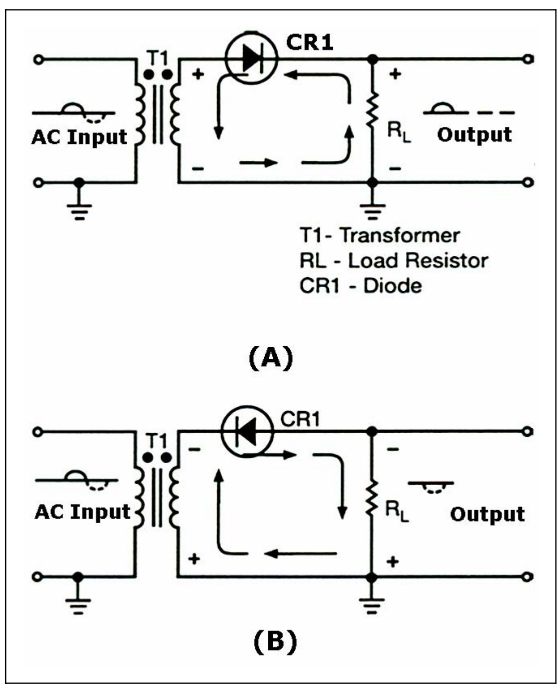
REVERSE BIAS - an external voltage that is connected across a PN junction so that its voltage aids the junction and thereby offers a high resistance to the current flow through the junction.



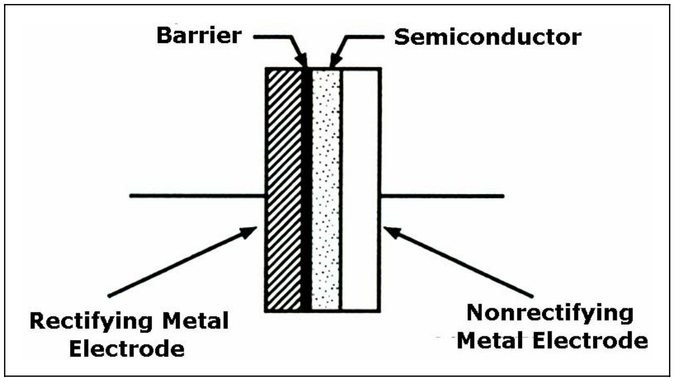
PN JUNCTION **-** a unique ability to offer very little resistance to current flow in the forward-bias direction but maximum resistance to current flow when reverse biased. For this reason, the PN junction is commonly used as a diode to convert AC to DC.



PN JUNCTION'S APPLICATION **-** expands many different areas (from a simple voltage protection device to an amplifying diode). Two of the most commonly used applications for the PN junction are the SIGNAL DIODE (mixing, detecting, and switching signals) and the RECTIFYING DIODE (converting AC to DC).



METALLIC RECTIFIER - or dry-disc rectifier is a metal-to-semiconductor device that acts just like a diode in that it permits current to flow more readily in one direction than the other. Metallic rectifiers are used in many applications where a relatively large amount of power is required.



DIODE CHARACTERISTICS - the information supplied by manufacturers on different types of diodes. This information is supplied either in their manuals or on specification sheets.

DIODE RATINGS - the limiting values of operating conditions of a diode. Operation of the diode outside of its operating limits could damage the diode. Diodes are generally rated for the following: MAXIMUM AVERAGE FORWARD CURRENT, PEAK RECURRENT FORWARD CURRENT, MAXIMUM SURGE CURRENT, and PEAK REVERSE VOLTAGE.

SEMICONDUCTOR IDENTIFICATION SYSTEM - an alphanumerical code used to distinguish one semiconductor from another. It is used for diodes, transistors, and many other special semiconductor devices.

XNYYY

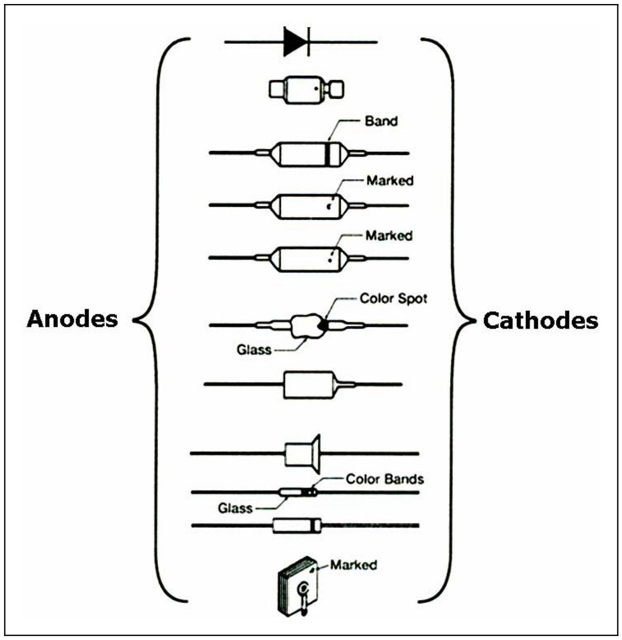
XN — **Component**

YYY — **Identification Number**

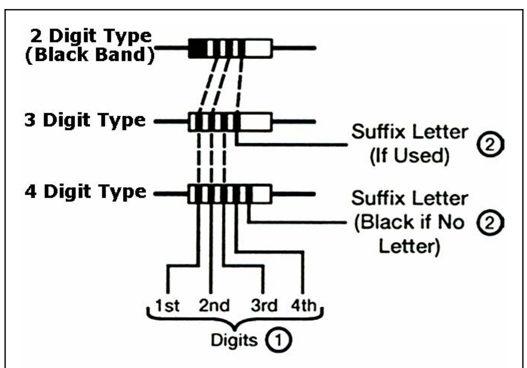
X - Number of Semiconductor Junctions
N - Semiconductor
YYY - Identification Number (Order or Registration Number)
Also Includes Suffix Letter (If Applicable) to Indicate:
1. Matching Devices
2. Reverse Polarity
3. Modification

Example - IN345A (an Improved Version of the Semiconductor Diode Type 345)

DIODE MARKINGS **-** letters and symbols placed on the diode by manufacturers to distinguish one end of the diode from the other. In some cases, an unusual shape or the addition of color code bands is used to distinguish the cathode from the anode.



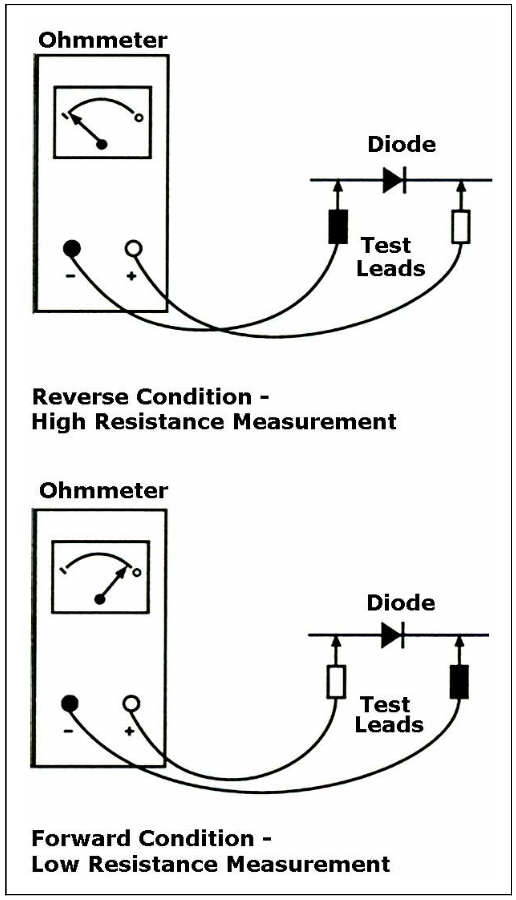
STANDARD DIODE COLOR CODE SYSTEM **-** serves two purposes when it is used: (1) identifies the cathode end of the diode, and (2) identifies the diode by number.



Color	1 Digit	2 Diode Suffix Letter
Black	0	-
Brown	1	A
Red	2	B
Orange	3	C
Yellow	4	D
Green	5	E
Blue	6	F
Violet	7	G
Gray	8	H
White	9	J
Silver	-	-
Gold	-	-
None	-	-

DIODE MAINTENANCE - the procedures or methods used to keep a diode in good operating condition. To prevent diode damage, you should observe standard diode safety precautions and ensure that diodes are not subjected to heat, current overloads, and excessively high operating voltages.

TESTING A DIODE - can be done by using an ohmmeter, the substitution method, or a dynamic diode tester. The most convenient and quickest way of testing a diode is with an ohmmeter.



CHAPTER 1
CHECK-ON-LEARNING QUESTIONS

When you are satisfied that you have answered every question to the best of your ability, check your answers using Appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. What is a solid state device?

2. How would you define the term negative temperature coefficient?

3. Semiconductor are used extensively in what three areas?

4. What is the life expectancy of transistors compared to ordinary electron tubes?

5. What are the three different states of matter?

6. What is the smallest particle into which an element can be broken down and still retain all its original properties?

7. An atom is basically composed of what?

8. What do you call the outer shell of an atom?

9. What is a negative ion?

10. An electron can exist in what two energy bands?

11. What determines, in terms of energy bands, whether a substance is a good insulator, semiconductor, or conductor?

12. What determines the chemical activity of an atom?

13. An atom has a complete outer shell when it posses how many valence electrons?

14. What is the term to describe the sharing of valence electrons between two or more atoms?

15. What is the name given to the movement of electrons in a semiconductor?

16. What is the purpose of semiconductor doping?

17. When can a N-type impurity easily lose its extra valence electron?

18. Pure germanium may be converted into a N-type semiconductor by doping it with what?

19. What is the purpose of a PN junction diode?

20. The semiconductor should be in how many pieces to form a proper PN junction?

21. What type of PN diode is formed by using a fine metal wire and a section of N-type semiconductor material?

22. Conduction in which type of semiconductor material is similar to conduction in a copper wire?

23. Instead of negative electrons, conduction in the P-type material is by what?

24. What is the name of the area in a PN junction that has a shortage of electrons and holes?

25. What terminal of a battery is connected to the P-type material in order to reverse bias a junction diode?

26. What is the name of the simplest rectifier circuit?

27. What is a load?

28. What happens to the depletion region when reverse bias is applied to a diode?

29. What type of rectifier is constructed by sandwiching a section of semiconductor material between two metal plates?

30. What type of bias makes a diode act as a closed switch?

31. What is used to show how diode parameters vary over a full operating range?

32. What is meant by diode ratings?

33. What is the greatest danger to a diode?

34. When would you use the substitution method for checking a diode?

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Chapter 2
Transistors

LEARNING OBJECTIVES

Learning objectives serve as a preview of the information you are expected to learn in this chapter. The comprehensive check-on-learning questions, found at the end of the chapter, are based on the objectives. Upon completion of this chapter, you will be able to perform the following learning objectives:

- Define the term "transistor" and give a brief description of its construction and operation.
- Explain how the transistor can be used to amplify a signal.
- Name the four classes of amplifiers and give an explanation for each.
- List the three different transistor circuit configurations and explain their operation.
- Identify the different types of transistors by their symbolism and alphanumerical designations.
- List the precautions to be taken when working with transistors and describe ways to test them.
- Explain the meaning of the expression "integrated circuits."
- Give a brief description on how ICs are constructed and the advantages they offer over conventional transistor circuits.
- Name the two types of circuit boards.
- State the purpose and function of modular circuitry.

INTRODUCTION TO TRANSISTORS

2-1. The discovery of the first transistor in 1948 by a team of physicists at the Bell Telephone Laboratories sparked an interest in solid state research that spread rapidly. The transistor, which began as a simple laboratory oddity, was rapidly developed into a semiconductor device of major importance. The transistor demonstrated for the first time in history that amplification in solids was possible. Prior to the transistor, amplification was achieved only with electron tubes. Transistors now perform many electronic tasks with new and improved transistor designs being continually put on the market. In many cases, transistors are more desirable than tubes because they are small, rugged, require no filament power, and operate at low voltages with comparatively high efficiency. The development of a family of transistors has even made possible the miniaturization of electronic circuits. Figure 2-1 shows a sample of the many different types of transistors you may encounter when working with electronic equipment.

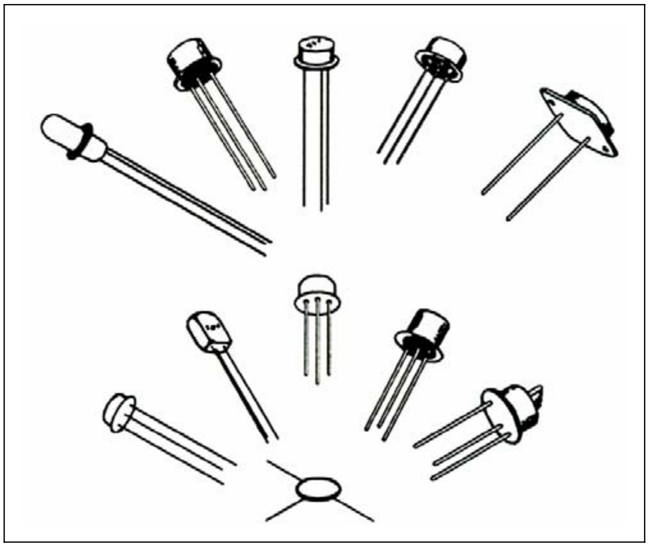


Figure 2-1. Assortment of Different Types of Transistors

2-2. Transistors are used in many areas of science and industry (from the family car to satellites). The military depends heavily on transistors. The ever-increasing uses for transistors have created an urgent need for sound and basic information regarding their operation.

2-3. After learning about the PN junction diode in chapter 1, you should have the basic knowledge on how to grasp the principles of transistor operation. This chapter will discuss the basic types of transistors, their construction, and their theory of operation. It also discusses how and why transistors amplify. This chapter also covers transistor terminology, capabilities, limitations, and identification; transistor maintenance; ICs; circuit boards; and modular circuitry.

TRANSISTOR FUNDAMENTALS

2-4. The first solid state device covered in chapter 1 was the two-element semiconductor diode. The next device we will cover not only has one more element than the diode but it can amplify as well. Semiconductor devices that have three or more elements are called TRANSISTORS. The term transistor was derived from the words TRANSFER and RESISTOR. This term was adopted because it best describes the operation of the transistor. The operation of the transistor is the transfer of an input signal current from a low-resistance circuit to a high-resistance circuit. The transistor is basically a solid state device that amplifies by controlling the flow of current carriers through its semiconductor materials.

2-5. There are many different types of transistors, but their basic theory of operation is the same. The theory we will use to explain the operation of a transistor is the same theory used earlier with the PN junction diode. The exception is that now two such junctions are required to form the three elements of a transistor. The three elements of the two-junction transistor are as follows:

- The EMITTER, which gives off or "emits" current carriers (electrons or holes).
- The BASE, which controls the flow of current carriers.
- The COLLECTOR, which collects the current carriers.

CLASSIFICATION

2-6. Transistors are classified, according to the arrangement of their N and P materials, as either NPN or PNP. Their basic construction and chemical treatment is implied by their names "NPN" or "PNP." That is, an NPN transistor is formed by introducing a thin region of P-type material between two regions of N-type material. However, a PNP transistor is formed by introducing a thin region of N-type material between two regions of P-type material. Transistors constructed in this manner have two PN junctions (see Figure 2-2). One PN junction is between the emitter and the base and the other PN junction is between the collector and the base. The two junctions share one section of semiconductor material so that the transistor actually consists of three elements.

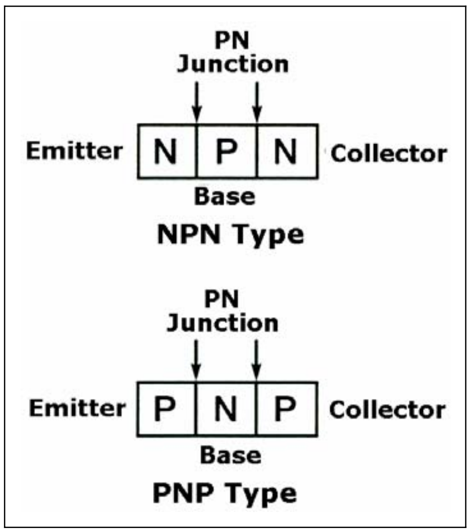


Figure 2-2. Transistor Block Diagrams

2-7. Since the majority and minority current carriers are different for N- and P-type materials, then it stands to reason that the internal operation of the NPN and PNP transistors will also be different. The theory of operation of the NPN and PNP transistors will be covered separately. Any additional information about the PN junction will be given as the theory of transistor operation is developed.

2-8. Figure 2-3 shows the two basic types of transistors along with their circuit symbols. Notice that the two symbols are different. The horizontal line represents the base, the angular line with the arrow on it represents the emitter, and the other angular line represents the collector. The direction of the arrow on the emitter distinguishes the NPN from the PNP transistor. If the arrow points in, the transistor is a PNP (Points iN Permanently). If the arrow points out, the transistor is an NPN (Not Pointing iN).

2-9. Remember that the arrow always points in the direction of hole flow or from the P to N sections (no matter whether the P section is the emitter or base) However, electron flow is always toward or against the arrow, just like in the junction diode.

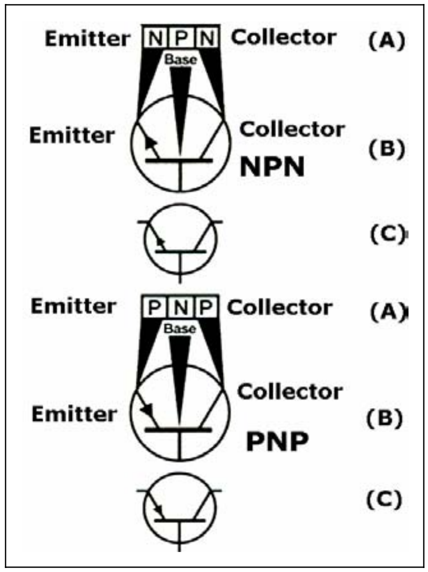


Figure 2-3. Transistor Representations

CONSTRUCTION

2-10. The very first transistors were known as point-contact transistors. Their construction is similar to the construction of the point-contact diode covered in chapter 1. The difference is that the point-contact transistor has two P or N regions formed instead of one. Each of the two regions constitutes an electrode (element) of the transistor. One is named the emitter and the other is named the collector (see Figure 2-4, view (A)).

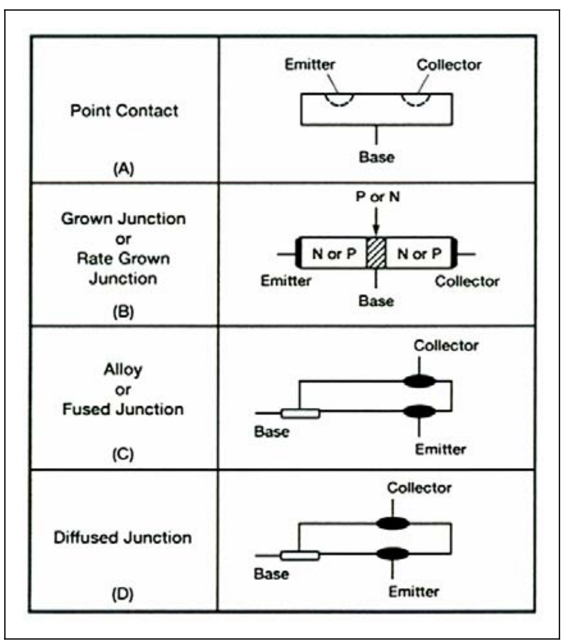


Figure 2-4. Transistor Constructions

2-11. Point-contact transistors are now practically obsolete. They have been replaced by junction transistors, which are superior to point-contact transistors in nearly all respects. The junction transistor generates less noise, handles more power, provides higher current

and voltage gains, and can be mass-produced more cheaply than the point-contact transistor. Junction transistors are manufactured in much the same manner as the PN junction diode covered in chapter 1. However, when the PNP or NPN material is grown (see Figure 2-4, view (B)), the impurity mixing process must be reversed twice in order to obtain the two junctions required in a transistor. Likewise, when the alloy junction (view (C)) or the diffused junction (view (D)) process is used, two junctions must also be created within the crystal.

2-12. Although there are many ways to manufacture transistors, one of the most important parts of any manufacturing process is quality control. Without good quality control, many transistors would prove unreliable because the construction and processing of a transistor govern its thermal ratings, stability, and electrical characteristics. Even though there are many variations in the transistor manufacturing processes, certain structural techniques, which yield good reliability and long life, are common to all processes. These techniques include the following:

- Wire leads are connected to each semiconductor electrode.
- The crystal is specially mounted to protect it against mechanical damage.
- The unit is selected to prevent harmful contamination of the crystal.

TRANSISTOR THEORY

2-13. Chapter 1 covered how a forward-biased PN junction is comparable to a low-resistance circuit element because it passes a high current for a given voltage. In turn, a reverse-biased PN junction is comparable to a high-resistance circuit element. By using the Ohm's law formula for power ($P = I^2R$) and assuming current is held constant, you can conclude that the power developed across a high resistance is greater than that developed across a low resistance. Therefore, if a crystal were to contain two PN junctions (one forward-biased and the other reverse-biased), a low-power signal could be injected into the forward-biased junction and produce a high-power signal at the reverse-biased junction. In this manner, a power gain would be obtained across the crystal. This concept, which is merely an extension of the material covered in chapter 1, is the basic theory behind how the transistor amplifies.

NPN Transistor Operation

2-14. As in the PN junction diode, the N-type material that makes up the two end sections of the NPN transistor contains a number of free electrons. The center P section contains an excess number of holes. The action at each junction between these sections is the same as that previously described for the diode; that is, depletion regions develop and the junction barrier appears. Each of these junctions must be modified by some external bias voltage in order to use the transistor as an amplifier. For the transistor to function in this capacity, the first PN junction (emitter-base junction) is biased in the forward or low-resistance direction. At the same time, the second PN junction (base-collector junction) is biased in the reverse, or high-resistance direction. A simple way to remember how to properly bias a transistor is to observe the NPN or PNP elements that make up the transistor. The letters of these elements indicate what polarity voltage to use for correct bias. The emitter, which is the first letter in the NPN sequence, is connected to the negative side of the battery while the base, which is the second letter (NPN), is connected to the positive side (see Figure 2-5). Since the second PN junction is required to be reverse biased for proper transistor operation, then the collector must be connected to an opposite polarity

voltage (positive) than that indicated by its letter designation (NPN). The voltage on the collector must also be more positive than the base (see Figure 2-6).

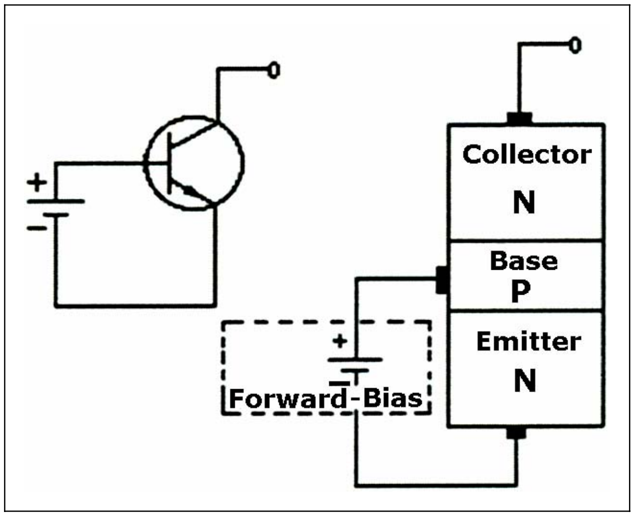


Figure 2-5. NPN Transistor (Forward Bias)

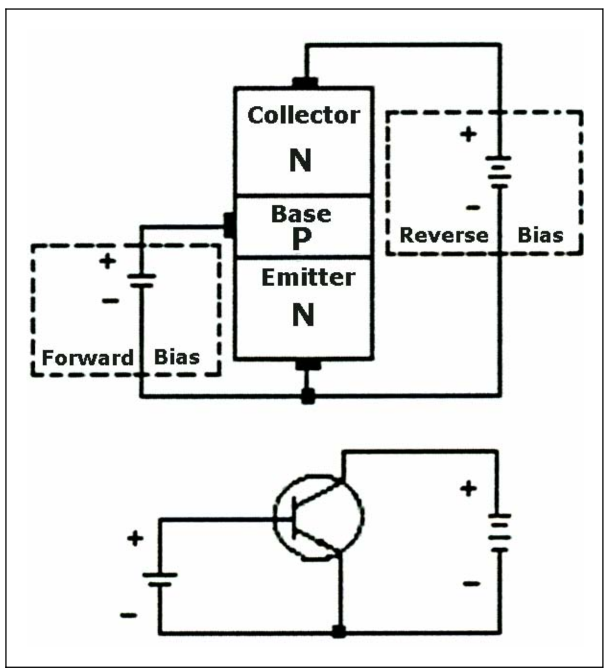


Figure 2-6. NPN Transistor (Reverse Bias)

2-15. We now have a properly biased NPN transistor. Remember, the base of the NPN transistor must be positive with respect to the emitter and the collector must be more positive than the base.

2-16. NPN FORWARD-BIASED JUNCTION - An important point to bring out at this time is the fact that the N-type material on one side of the forward-biased junction is more heavily doped than the P-type material. This results in more current being carried across the junction by the majority carrier electrons from the N-type material than the majority carrier holes from the P-type material. Therefore, conduction through the forward-biased

junction (see Figure 2-7) is mainly by majority carrier electrons from the N-type material (emitter).

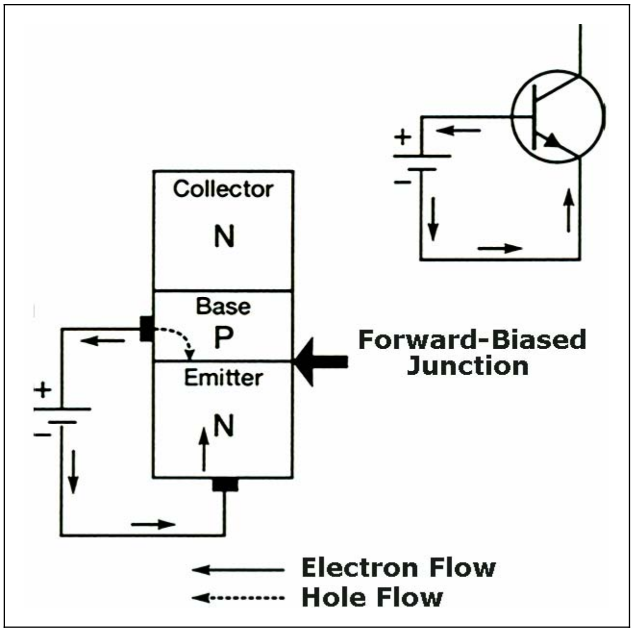


Figure 2-7. Forward-biased Junction in an NPN Transistor

2-17. With the emitter-to-base junction in the figure biased in the forward direction, electrons leave the negative terminal of the battery and enter the N-type material (emitter). Since electrons are majority current carriers in the N-type material, they pass easily through the emitter, cross over the junction, and combine with holes in the P-type material (base). For each electron that fills a hole in the P-type material, another electron will leave the P-type material (creating a new hole) and enter the positive terminal of the battery.

2-18. NPN REVERSE-BIASED JUNCTION - The second PN junction (base-to-collector) or reverse-biased junction as it is called (see Figure 2-8), blocks the majority current carriers from crossing the junction. However, there is a very small current, mentioned earlier, that does pass through this junction. This current is called minority current or reverse current. Remember, the electron hole pairs produced this current. The minority carriers for the reverse-biased PN junction are the electrons in the P-type material and the holes in the N-type material. These minority carriers actually conduct the current for the reverse-biased junction when electrons from the P-type material enter the N-type material, and the holes from the N-type material enter the P-type material. However, the minority current electrons (as you will see later) play the most important part in the operation of the NPN transistor.

2-19. You may be wondering why the second PN junction (base-to-collector) is not forward biased like the first PN junction (emitter-to-base). If both junctions were forward biased, the electrons would have a tendency to flow from each end section of the N P N transistor (emitter and collector) to the center P section (base). In essence, we would have two junction diodes possessing a common base, thereby eliminating any amplification and defeating the purpose of the transistor. A word of caution, if you should mistakenly bias the second PN junction in the forward direction. The excessive current could develop

enough heat to destroy the junctions, making the transistor useless. Therefore, be sure your bias voltage polarities are correct before making any electrical connections.

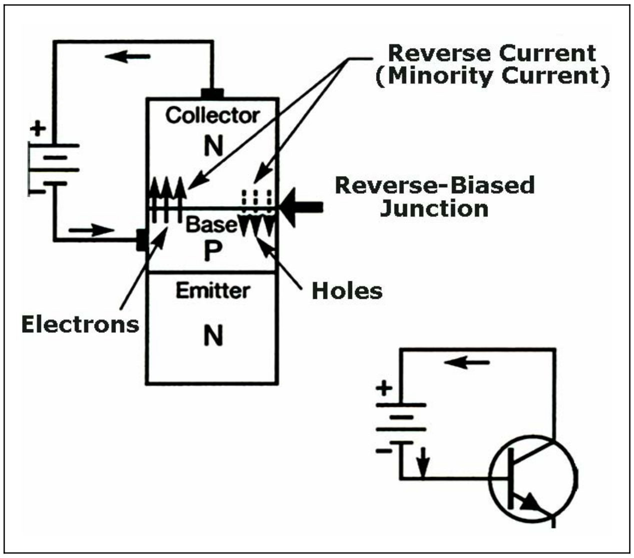


Figure 2-8. Reverse-biased Junction in an NPN Transistor

2-20. NPN JUNCTION INTERACTION - We are now ready to see what happens when we place the two junctions of the NPN transistor in operation at the same time. See Figure 2-9 for a better understanding of just how the two junctions work together.

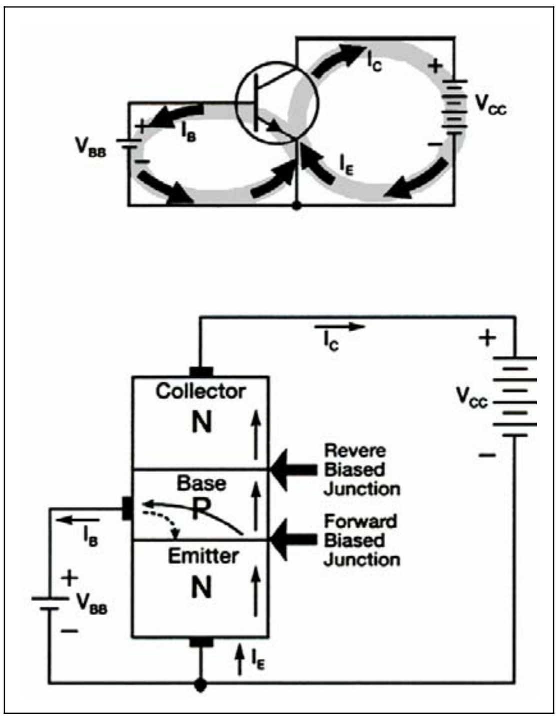


Figure 2-9. NPN Junction Interaction Transistor Operation

2-21. The bias batteries in this figure have been labeled V_{CC} for the collector voltage supply and V_{BB} for the base voltage supply. Also notice the base supply battery is quite small, as indicated by the number of cells in the battery, usually 1 volt or less. However, the collector supply is generally much higher than the base supply (normally around 6 volts). Later you will see that this difference in supply voltages is necessary in order to have current flow from the emitter to the collector.

2-22. As stated earlier, the current flow in the external circuit is always due to the movement of free electrons. Therefore, electrons flow from the negative terminals of the supply batteries to the N-type emitter. This combined movement of electrons is known as emitter current (I_E). Since electrons are the majority carriers in the N-type material, they will move through the N-type material emitter to the emitter-base junction. With this junction forward biased, electrons continue on into the base region. Once the electrons are in the base, which is a P-type material, they now become minority carriers. Some of the electrons that move into the base recombine with available holes. For each electron that recombines, another electron moves out through the base lead as base current I_B (creating a new hole for eventual combination) and returns to the base supply battery V_{BB}. The electrons that recombine are lost as far as the collector is concerned. Therefore, in order to make the transistor more efficient, the base region is made very thin and lightly doped. This reduces the opportunity for an electron to recombine with a hole and be lost. So, most of the electrons that move into the base region come under the influence of the large collector reverse bias.

2-23. This bias acts as forward bias for the minority carriers (electrons) in the base and, as such, accelerates them through the base-collector junction and on into the collector region. Since the collector is made of an N-type material, the electrons that reach the collector again become majority current carriers. Once in the collector, the electrons move easily through the N-type material and return to the positive terminal of the collector supply battery V_{CC} as collector current (I_C).

2-24. To further improve on the efficiency of the transistor, the collector is made physically larger than the base for the following reasons:

- To increase the chance of collecting carriers that diffuses to the side as well as directly across the base region.
- To enable the collector to handle more heat without damage.

2-25. Total current flow in the NPN transistor is through the emitter lead. Therefore, in terms of percentage, I_E is 100 percent. On the other hand, since the base is very thin and lightly doped, then a smaller percentage of the total current (emitter current) will flow in the base circuit than in the collector circuit. Usually no more than 2 to 5 percent of the total current is base current I_B while the remaining 95 to 98 percent is collector current (I_C). A very basic relationship exists between these two currents: $I_E = I_B + I_C$

2-26. In simpler terms, this means that the emitter current is separated into base and collector current. Since the amount of current leaving the emitter is solely a function of the emitter-base bias and because the collector receives most of this current, then a small change in emitter-base bias will have a far greater affect on the magnitude of collector current than it will have on base current. In conclusion, the relatively small emitter-base bias controls the relatively large emitter-to-collector current.

PNP Transistor Operation

2-27. The PNP transistor works essentially the same as the NPN transistor. However, since the emitter, base, and collector in the PNP transistor are made of materials that are different from those used in the NPN transistor, different current carriers flow in the PNP unit. The majority current carriers in the PNP transistor are holes. This is in contrast to the NPN transistor where the majority current carriers are electrons. In order to support this different type of current (hole flow), the bias batteries are reversed for the PNP transistor. Figure 2-10 shows a typical bias setup for the PNP transistor. Notice that the procedure used earlier to properly bias the NPN transistor also applies here to the PNP transistor. The first letter (P) in the PNP sequence indicates the polarity of the voltage required for the emitter (positive) and the second letter (N) indicates the polarity of the base voltage (negative). Since the base-collector junction is always reverse biased, then the opposite polarity voltage (negative} must be used for the collector. Therefore, the base of the PNP transistor must be negative with respect to the emitter and the collector must be more negative than the base. Just as in the case of the NPN transistor, this difference in supply voltage is necessary in order to have current flow (hole flow in the case of the PNP transistor) from the emitter to the collector. Although hole flow is the predominant type of current flow in the PNP transistor, hole flow only takes place within the transistor itself, while electrons flow in the external circuit. However, it is the internal hole flow that leads to electron flow in the external wires connected to the transistor.

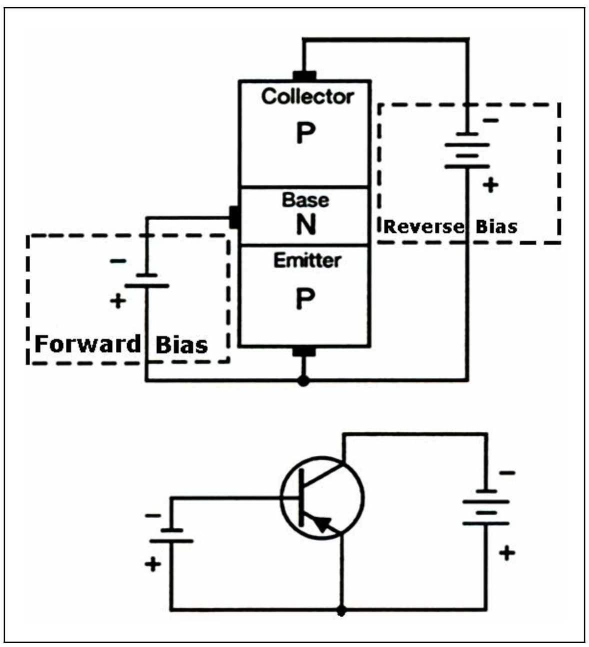


Figure 2-10. Properly Biased PNP Transistor

2-28. PNP FORWARD-BIASED JUNCTION - Now let use consider what happens when the emitter-base junction is forward biased (see Figure 2-11). With the bias setup shown, the positive terminal of the battery repels the emitter holes toward the base, while the negative terminal drives the base electrons toward the emitter. When an emitter hole and a base electron meet, they combine. For each electron that combines with a hole, another electron leaves the negative terminal of the battery, and enters the base. At the same time, an electron leaves the emitter, creating a new hole, and enters the positive

terminal of the battery. This movement of electrons into the base and out of the emitter constitutes base current flow (I_B) and the path these electrons take is referred to as the emitter-base circuit.

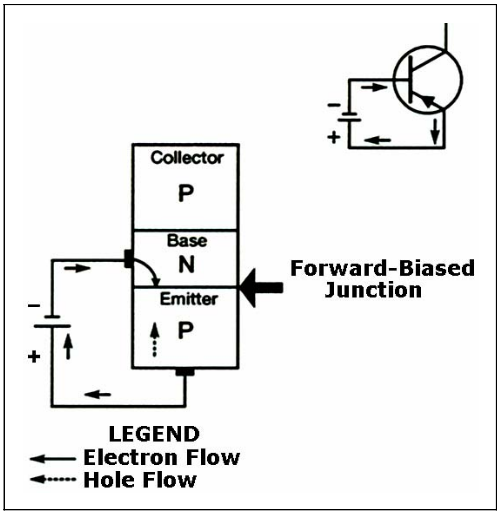


Figure 2-11. Forward-biased Junction in a PNP Transistor

2-29. PNP REVERSE-BIASED JUNCTION - In the reverse-biased junction (see Figure 2-12), the negative voltage on the collector and the positive voltage on the base, block the majority current carriers from crossing the junction. However, this same negative collector voltage acts as forward bias for the minority current holes in the base, which cross the junction and enter the collector. The minority current electrons in the collector also sense forward bias (the positive base voltage) and move into the base. Electrons that flow from the negative terminal of the battery fill the holes in the collector. At the same time the electrons leave the negative terminal of the battery, other electrons in the base break their covalent bonds and enter the positive terminal of the battery. Although there is only minority current flow in the reverse-biased junction, it is still very small due to the limited number of minority current carriers.

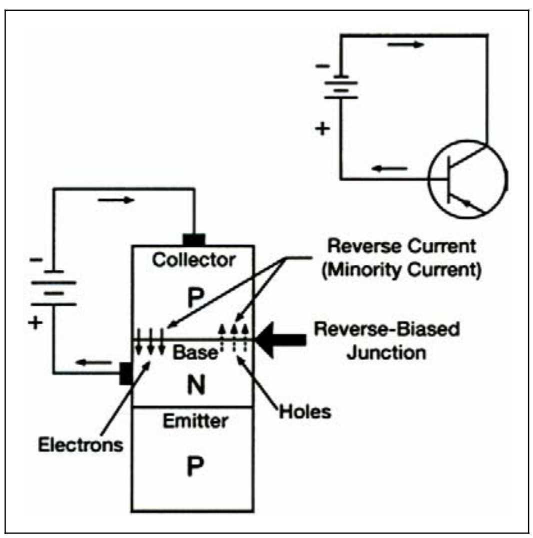


Figure 2-12. Reversed-biased Junction in a PNP Transistor

2-30. PNP JUNCTION INTERACTION - The interaction between the forward- and reverse-biased junctions in a PNP transistor is very similar to that in an NPN transistor. The difference is that in the PNP transistor, the majority current carriers are holes. In the PNP transistor (see Figure 2-13), the positive voltage on the emitter repels the holes toward the base. Once in the base, the holes combine with base electrons. Remember that the base region is made very thin to prevent the recombination of holes with electrons. Therefore, well over 90 percent of the holes that enter the base become attracted to the large negative collector voltage and pass right through the base. However, for each electron and hole that combines in the base region, another electron leaves the negative terminal of the base battery (V_{BB}) and enters the base as base current (I_B). At the same time an electron leaves the negative terminal of the battery, another electron leaves the emitter as I_E (creating a new hole) and enters the positive terminal of V_{BB}. Meanwhile, in the collector circuit, electrons from the collector battery (V_{CC}) enter the collector as I_C and combine with the excess holes from the base. For each hole that is neutralized in the collector by an electron, another electron leaves the emitter and starts its way back to the positive terminal of V_{CC}.

2-31. Although current flow in the external circuit of the PNP transistor is opposite in direction to that of the NPN transistor, the majority carriers always flow from the emitter to the collector. This flow of majority carriers also results in the formation of two individual current loops within each transistor. One loop is the base-current path and the other loop the collector-current path. The combination of the current in both of these loops (I_B + I_C) results in total transistor current (I_E). The most important thing to remember about the two different types of transistors is that the emitter-base voltage of the PNP transistor has the same controlling affect on collector current as that of the NPN transistor. In simple terms, increasing the forward-bias voltage of a transistor reduces the emitter-base junction barrier. This action allows more carriers to reach the collector causing an increase in current flow from the emitter to the collector and through the external circuit. A decrease in the forward-bias voltage reduces collector current.

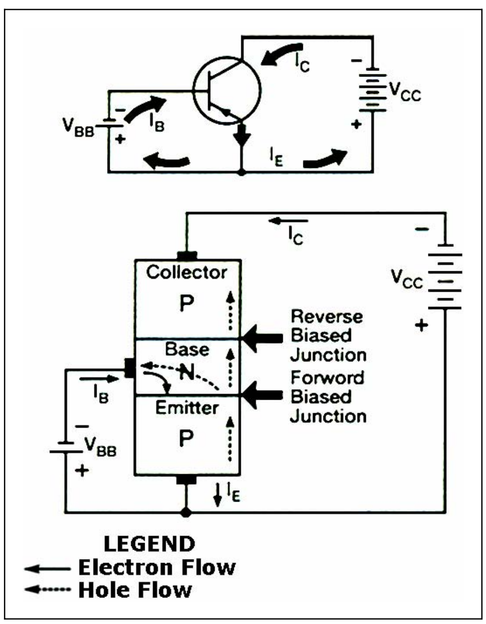


Figure 2-13. PNP Junction Interaction Transistor Operation

THE BASIC TRANSISTOR AMPLIFIER

2-32. To understand the overall operation of the transistor amplifier, you must only consider the current going in and out of the transistor and through the various components in the circuit. Therefore, from this point on, only the schematic symbol for the transistor will be used in the illustrations. Rather than thinking about majority and minority carriers, we will think in terms of emitter, base, and collector current.

2-33. There are two terms you should be familiar with before learning about the basic transistor amplifier. These two terms are AMPLIFICATION and AMPLIFIER. Amplification is the process of increasing the strength of a SIGNAL. A signal is just a general term used to refer to any particular current, voltage, or power in a circuit. An amplifier is the device that provides amplification (the increase in current, voltage, or power of a signal) without appreciably altering the original signal.

2-34. Transistors are frequently used as amplifiers. Some transistor circuits are CURRENT amplifiers, which have a small load resistance. Other circuits are designed for VOLTAGE amplification, which have a high load resistance. Still other circuits amplify POWER. Figure 2-14 shows an NPN version of the basic transistor amplifier.

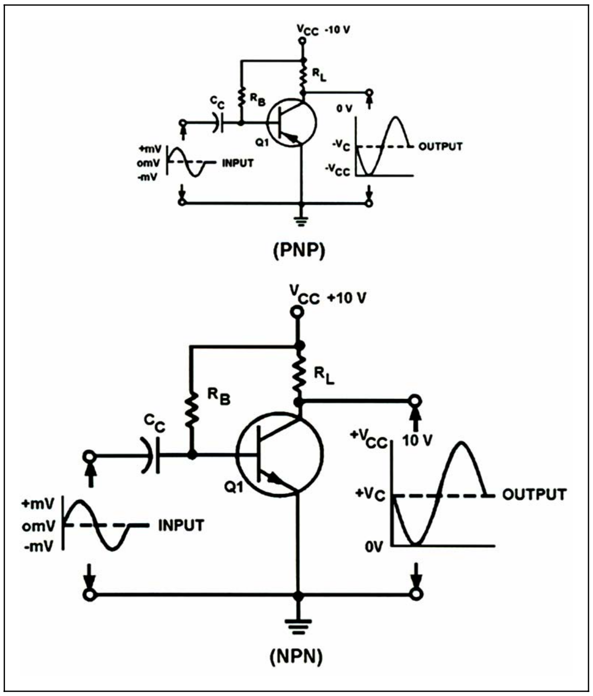


Figure 2-14. Basic Transistor Amplifier

2-35. So far we have covered how a separate battery has been used to provide the necessary forward-bias voltage. Although a separate battery has been used in the past for convenience, it is not practical to use a battery for emitter-base bias. For instance, it would take a battery slightly over .2 volts to properly forward bias a germanium transistor while a similar silicon transistor would require a voltage slightly over .6 volts. However, common batteries do not have such voltage values. Since bias voltages are quite critical and must be held within a few tenths of one volt, it is easier to work with bias currents flowing through resistors of high ohmic values than with batteries.

2-36. By inserting one or more resistors in a circuit, different methods of biasing may be achieved and the emitter-base battery eliminated. In addition to eliminating the battery, some of these biasing methods compensate for slight variations in transistor characteristics and changes in transistor conduction resulting from temperature irregularities. Notice in Figure 2-14 that the emitter-base battery has been eliminated and the bias resistor (R_B) has been inserted between the collector and the base. Resistor R_B provides the necessary forward bias for the emitter-base junction. Current flows in the emitter-base bias circuit from ground to the emitter, out the base lead, and through R_B to V_{CC}. Since the current in the base circuit is very small (a few hundred microamperes) and the forward resistance of the transistor is low, only a few tenths of a volt of positive bias will be felt on the base of the transistor. However, this is enough voltage on the base, along with ground on the emitter and the large positive voltage on the collector, to properly bias the transistor.

2-37. With Q1 properly biased, DC flows continuously, with or without an input signal, throughout the entire circuit. The DC flowing through the circuit develops more than just base bias; it also develops the collector voltage (V_C) as it flows through Q1 and R_L. Notice the collector voltage on the output graph. Since it is present in the circuit without an input signal, then the output signal starts at the V_C level and either increases or decreases. These DC voltages and currents that exist in the circuit prior to the application of a signal are known as QUIESCENT voltages and currents (the quiescent state of the circuit).

2-38. Resistor R_L, the collector load resistor, is placed in the circuit to keep the full affect of the collector supply voltage off the collector. This permits the collector voltage (V_C) to change with an input signal, which in turn allows the transistor to amplify voltage. Without R_L in the circuit, the voltage on the collector would always be equal to V_{CC}.

2-39. The coupling capacitor (C_C) is another new addition to the transistor circuit. It is used to pass the AC input signal and block the DC voltage from the preceding circuit. This prevents DC in the circuitry on the left of the coupling capacitor from affecting the bias on Q1. The coupling capacitor also blocks the bias of Q1 from reaching the input signal source.

2-40. The input to the amplifier is a sine wave that varies a few millivolts above and below zero. It is introduced into the circuit by the coupling capacitor and is applied between the base and emitter. As the input signal goes positive, the voltage across the emitter-base junction becomes more positive. This in effect increases forward bias that causes base current to increase at the same rate as that of the input sine wave. Emitter and collector currents also increase, but much more than the base current. With an increase in collector current, more voltage is developed across R_L. Since the voltage across R_L and the voltage across Q1 (collector to emitter) must add up to V_{CC}, an increase in voltage across R_L results in an equal decrease in voltage across Q1. Therefore, the output voltage from the amplifier, taken at the collector of Q1 with respect to the emitter, is a negative alternation of voltage that is larger than the input, but has the same sine wave characteristics.

2-41. During the negative alternation of the input, the input signal opposes the forward bias. This action decreases base current, which results in a decrease in both emitter and collector currents. The decrease in current through R_L decreases its voltage drop and causes the voltage across the transistor to rise along with the output voltage. Therefore, the output for the negative alternation of the input is a positive alternation of voltage that is larger than the input, but has the same sine wave characteristics. By examining both input and output signals for one complete alternation of the input, we can see that the output of the

amplifier is an exact reproduction of the input except for the reversal in polarity and the increased amplitude (a few millivolts as compared to a few volts).

2-42. Figure 2-14 shows the PNP version of the basic transistor amplifier. The primary difference between the NPN and PNP amplifier is the polarity of the source voltage. With a negative V_{CC}, the PNP base voltage is slightly negative with respect to ground, which provides the necessary forward bias condition between the emitter and base.

2-43. When the PNP input signal goes positive, it opposes the forward bias of the transistor. This action cancels some of the negative voltage across the emitter-base junction that reduces the current through the transistor. Therefore, the voltage across the load resistor decreases and the voltage across the transistor increases. Since V_{CC} is negative, the voltage on the collector (V_C) goes in a negative direction (as shown on the output graph) toward $-V_{CC}$ (for example from -5 volts to -7 volts). Therefore, the output is a negative alternation of voltage that varies at the same rate as the sine wave input but is opposite in polarity and has a much larger amplitude.

2-44. During the negative alternation of the input signal, the transistor current increases because the input voltage aids the forward bias. Therefore, the voltage across R_L increases, and consequently, the voltage across the transistor decreases or goes in a positive direction (for example from -5 volts to -3 volts). This action results in a positive output voltage, which has the same characteristics as the input except that it has been amplified and the polarity is reversed.

2-45. The input signals in the preceding circuits were amplified because the small change in base current caused a large change in collector current. By placing resistor R_L in series with the collector, voltage amplification was achieved.

TYPES OF BIAS

2-46. One of the basic problems with transistor amplifiers is establishing and maintaining the proper values of quiescent current and voltage in the circuit. This is accomplished by selecting the proper circuit-biasing conditions and ensuring these conditions are maintained despite variations in ambient (surrounding) temperature, which cause changes in amplification and even distortion (an unwanted change in a signal). Therefore, a need arises for a method to properly bias the transistor amplifier and at the same time stabilize its DC operating point (the no signal values of collector voltage and collector current). As mentioned earlier, various biasing methods can be used to accomplish both of these functions. Although there are many biasing methods, only the three basic types (base-current bias [fixed bias], self-bias, and combination bias) will be discussed.

Base-Current Bias (Fixed Bias)

2-47. The first biasing method, called BASE-CURRENT BIAS or sometimes FIXED BIAS, was used in Figure 2-14. This method consisted basically of a resistor (R_B) connected between the collector supply voltage and the base. Unfortunately, this simple arrangement is quite thermally unstable. If the temperature of the transistor rises for any reason (due to a rise in ambient temperature or due to current flow through it), collector current will increase. This increase in current also causes the DC operating point, sometimes called the quiescent or static point, to move away from its desired position (level). This reaction to temperature is undesirable because it affects amplifier gain (the number of times of amplification) and could result in distortion.

Self-Bias

2-48. A better method of biasing is obtained by inserting the bias resistor directly between the base and collector (see Figure 2-15). By tying the collector to the base in this manner, feedback voltage can be fed from the collector to the base to develop forward bias. This arrangement is called SELF-BIAS. If an increase of temperature causes an increase in collector current, the collector voltage (V_C) will fall due to the increase of voltage produced across the load resistor (R_L). This drop in V_C will be fed back to the base and will result in a decrease in the base current. The decrease in base current will oppose the original increase in collector current and tends to stabilize it. The exact opposite effect is produced when the collector current decreases.

2-49. Self-bias has two small drawbacks. One is that it is only partially effective and therefore, is only used where moderate changes in ambient temperature are expected. The second is that it reduces amplification since the signal on the collector also affects the base voltage. This is because the collector and base signals for this particular amplifier configuration are 180 degrees out of phase (opposite in polarity) and the part of the collector signal that is fed back to the base cancels some of the input signal. This process of returning a part of the output back to its input is known as DEGENERATION or NEGATIVE FEEDBACK. Sometimes degeneration is desired to prevent amplitude distortion (an output signal that fails to follow the input exactly) and self-bias may be used for this purpose.

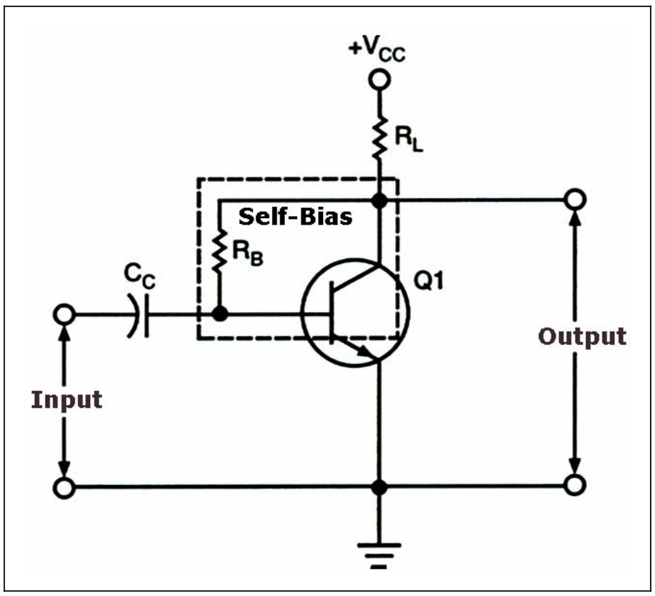


Figure 2-15. Basic Transistor Amplifier with Self-Bias

Combination Bias

2-50. A combination of fixed and self-bias can be used to improve stability and at the same time overcome some of the disadvantages of the other two biasing methods. One of the most widely used combination bias systems is the voltage-divider type (see Figure 2-16). Fixed bias is provided in this circuit by the voltage-divider network consisting of R1, R2, and the collector supply voltage (V_{CC}). The DC current flowing through the voltage-divider network biases the base positive with respect to the emitter. Resistor R3, which is connected in series with the emitter, provides the emitter with self-

bias. Should I_E increase, the voltage drop across R3 would also increase, reducing V_C. This reaction to an increase in I_E by R3 is another form of degeneration, which results in less output from the amplifier. However, to provide long-term or DC thermal stability and at the same time allow minimal AC signal degeneration, the bypass capacitor C_{BP} is placed across R3. If C_{BP} is large enough, rapid signal variations will not change its charge materially and no degeneration of the signal will occur.

2-51. The fixed-bias resistors (R1 and R2) tend to keep the base bias constant while the emitter bias changes with emitter conduction. This action greatly improves thermal stability and at the same time maintains the correct operating point for the transistor.

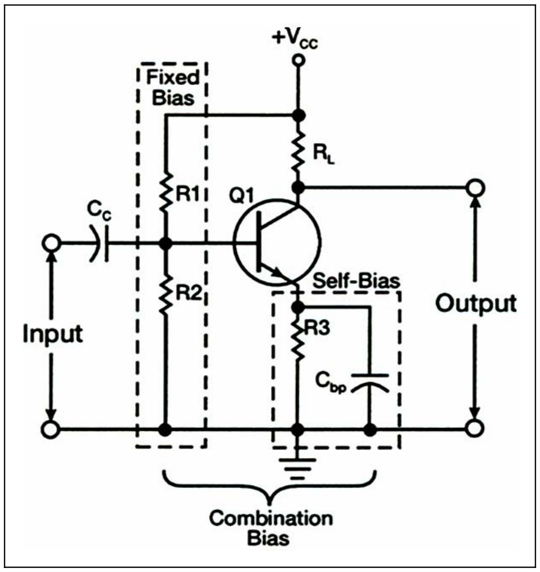


Figure 2-16. Basic Transistor Amplifier with Combination Bias

AMPLIFIER CLASSES OF OPERATION

2-52. Earlier in this chapter we assumed that for every portion of the input signal there was an output from the amplifier. This is not always the case with amplifiers. It may be desirable to have the transistor conducting for only a portion of the input signal. The portion of the input for which there is an output determines the class of operation of the amplifier. The following are the four classes of amplifier operations:

- Class A.
- Class AB.
- Class B.
- Class C.

Also refer to Figure 2-17 for a comparison of output signals for the different amplifier classes of operation.

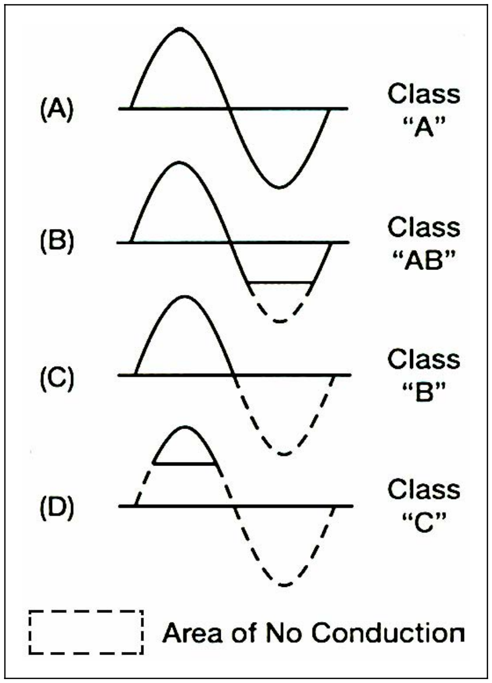


Figure 2-17. Comparison of Output Signals for the Different Amplifier Classes of Operation

Class A Amplifier Operation

2-53. Class A amplifiers are biased so that variations in input signal polarities occur within the limits of CUTOFF and SATURATION. For example, in a PNP transistor if the base becomes positive with respect to the emitter, holes will be repelled at the PN junction and no current can flow in the collector circuit. This condition is known as cutoff. Saturation occurs when the base becomes so negative with respect to the emitter that changes in the signal are not reflected in collector-current flow.

2-54. Biasing an amplifier in this manner places the DC operating point between cutoff and saturation. This allows collector current to flow during the complete cycle (360 degrees) of the input signal, thereby providing an output, which is a replica of the input. Although the output from this amplifier is 180 degrees out of phase with the input, the output current still flows for the complete duration of the input (see Figure 2-17, view (A)). The class A operated amplifier is used as an audio and RF amplifier in radio, radar, sound systems, and so forth.

Class AB Amplifier Operation

2-55. Amplifiers designed for class AB operation are biased so that collector current is zero (cutoff) for a portion of one alternation of the input signal. This is accomplished by making the forward-bias voltage less than the peak value of the input signal. By doing this, the base-emitter junction will be reverse biased during one alternation for the amount of time that the input signal voltage opposes and exceeds the value of forward-bias voltage. Therefore, collector current will flow for more than 180 degrees but less than 360 degrees of the input signal (see Figure 2-17, view (B)). Compared to the class A amplifier, the DC operating point for the class AB amplifier is closer to cutoff. The class AB operated amplifier is commonly used as a push-pull amplifier to overcome a side effect of class B operation called crossover distortion.

Class B Amplifier Operation

2-56. Amplifiers biased so that collector current is cut off during one-half of the input signal are classified class B. The DC operating point for this class of amplifier is set up so that base current is zero with no input signal. When a signal is applied, one half cycle will forward bias the base-emitter junction and I_C will flow. The other half cycle will reverse bias the base-emitter junction and I_C will be cut off. So, for class B operation, collector current will flow for approximately 180 degrees (half) of the input signal (see Figure 2-17, view (C)). The class B operated amplifier is used extensively for audio amplifiers that require high-power outputs. It is also used as the driver- and power-amplifier stages of transmitters.

Class C Amplifier Operation

2-57. In class C operation, collector current flows for less than one half cycle of the input signal (see Figure 2-17, view (D)). The class C operation is achieved by reverse biasing the emitter-base junction that sets the DC operating point below cutoff and allows only the portion of the input signal that overcomes the reverse bias to cause collector current flow. The class C operated amplifier is used as a RF amplifier in transmitters.

2-58. We already know that the two primary things that determine the class of operation are the amount of bias and the amplitude of the input signal. With a given input signal and bias level, you can change the operation of an amplifier from class A to class B just by removing forward bias. You can change a class A amplifier to a class AB amplifier by increasing the input signal amplitude. However, if the input signal amplitude is increased to the point that the transistor goes into saturation and cutoff, it is then called an OVERDRIVEN amplifier.

2-59. The two terms, used in conjunction with amplifiers, that you should be familiar with are FIDELITY and EFFICIENCY. Fidelity is the faithful reproduction of a signal. In other words, if the output of an amplifier is just like the input except in amplitude, the amplifier has a high degree of fidelity. The opposite of fidelity is distortion. A circuit that has high fidelity has low distortion. Therefore, a class A amplifier has a high degree of fidelity; a class AB amplifier has less fidelity; and class B and class C amplifiers have low or “poor” fidelity. The efficiency of an amplifier refers to the ratio of output-signal power compared to the total input power. An amplifier has two input power sources (one from the signal and one from the power supply). Since every device takes power to operate, an amplifier that operates for 360 degrees of the input signal uses more power than if operated for 180 degrees of the input signal. By using more power, an amplifier has less power available for the output signal; so the efficiency of the amplifier is low.

2-60. The class A amplifier operates for 360 degrees of the input signal and requires a relatively large input from the power supply. The class A amplifier, even with no input signal, still uses power from the power supply. Therefore, the output from the class A amplifier is relatively small compared to the total input power. The result of this is in low efficiency that is acceptable in class A amplifiers because they are used where efficiency is not as important as fidelity. Class AB amplifiers are biased so that collector current is cut off for a portion of one alternation of the input which results in less total input power than the class A amplifier. This leads to better efficiency. Class B amplifiers are biased with little or no collector current at the DC operating point. With no input signal, there is little wasted power. Therefore, the efficiency of class B amplifiers is higher still. The efficiency of class C is the highest of the four classes of amplifier operations.

TRANSISTOR CONFIGURATIONS

2-61. A transistor may be connected in any one of three basic configurations (see also Figure 2-18):

- Common emitter.
- Common base.
- Common collector.

The term "common" is used to denote the element that is common to both input and output circuits. Since the common element is often grounded, these configurations are frequently referred to as grounded emitter, grounded base, and grounded collector.

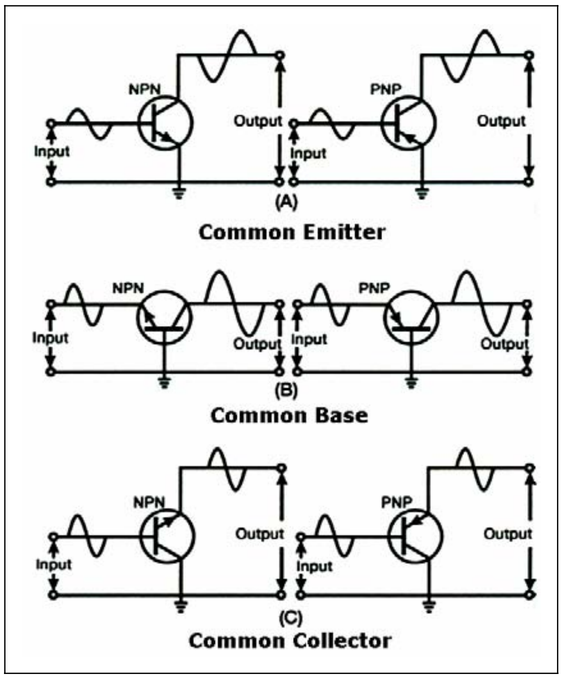


Figure 2-18. Transistor Configurations

2-62. Each configuration has certain characteristics that make it suitable for specific applications. An easy way to identify a specific transistor configuration is to follow three simple steps:

- **Step One -** Identify the element (emitter, base, or collector) to which the input signal is applied.
- **Step Two -** Identify the element (emitter, base, or collector) from which the output signal is taken.
- **Step Three -** The remaining element is the common element, which gives the configuration its name.

By applying these three simple steps to the circuit in Figure 2-14, we can conclude that this circuit is more than just a basic transistor amplifier; it is a CE amplifier.

Common Emitter

2-63. The CE configuration (see Figure 2-18, view (A)) is the arrangement most often used in practical amplifier circuits. This is because it provides good voltage, current, and power gain. The CE has a somewhat low input resistance (500 ohms to 1,500 ohms) because the input is applied to the forward-biased junction. The CE has a moderately high output resistance (30 kilohms to 50 kilohms or more) because the output is taken off the reverse-biased junction. Since the input signal is applied to the base-emitter circuit and the output is taken from the collector-emitter circuit, then the emitter is the element common to both input and output.

2-64. Using the PNP CE configuration (see Figure 2-18, view (A)), let us review the CE amplifier. When a transistor is connected in a CE configuration, the input signal is injected between the base and emitter, which is a low resistance, low-current circuit. As the input signal swings positive, it also causes the base to swing positive with respect to the emitter. This action decreases forward bias that reduces collector current (I_C) and increases collector voltage (making V_C more negative). During the negative alternation of the input signal, the base is driven more negative with respect to the emitter. This increases forward bias and allows more current carriers to be released from the emitter. This results in an increase in collector current and a decrease in collector voltage (making V_C less negative or swing in a positive direction). The collector current that flows through the high resistance reverse-biased junction also flows through a high resistance load (not shown), resulting in a high level of amplification.

2-65. Since the input signal to the CE goes positive when the output goes negative, the two signals (input and output) are 180 degrees out of phase. The CE circuit is the only configuration that provides a phase reversal.

2-66. The CE is the most popular of the three transistor configurations because it has the best combination of current and voltage gain. The term GAIN is used to describe the amplification capabilities of the amplifier. It is basically a ratio of the following:

$$\frac{\text{output}}{\text{input}}$$

Each transistor configuration gives a different value of gain even though the same transistor is used. The transistor configuration used is a matter of design consideration. However, as a technician you will become interested in this output versus input ratio (gain) in order to determine whether or not the transistor is working properly in the circuit.

2-67. The current gain in the CE circuit is called BETA (β). Beta is the relationship of collector current (output current) to base current (input current). Use the following formula to calculate beta:

$$\beta = \frac{\Delta I_C}{\Delta I_C}$$ (Δ is the Greek letter delta, it is used to indicate a small change)

For example, if the input current (I_B) in a CE changes from 75 µA to 100 µA and the output current (I_C) changes from 1.5 mA to 2.6 mA, then the current gain (β) would be 44.

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{1.1 \ \text{x} \ 10^{-3}}{25 \ \text{x} \ 10^{-6}} = 44$$

This simply means that a change in base current produces a change in collector current that is 44 times as large.

2-68. You may also see the term h_{fe} used in place of β. The terms h_{fe} and β are equivalent and may be used interchangeably. This is because "h_{fe}" means:

h = hybrid (meaning mixture)
f = forward current transfer ratio
e = common emitter configuration

2-69. The resistance gain of the CE can be found in a method similar to the one used for finding beta:

$$R = \frac{R_{OUT}}{R_{IN}}$$

2-70. Once the resistance gain is known, the voltage gain is easy to calculate since it is equal to the current gain β multiplied by the resistance gain (E = βR). The power gain is equal to the voltage gain multiplied by the current gain β (P = βE).

Common Base

2-71. The CB configuration (see Figure 2-17, view (B)) is mainly used for impedance matching, since it has a low input resistance (30 ohms to 160 ohms) and a high output resistance (250 kilohms to 550 kilohms). However, two factors that limit its usefulness in some circuit applications are its low input resistance and its current gain of less than 1. Since the CB configuration will give voltage amplification, there are some additional applications that require both a low-input resistance and voltage amplification. Some microphone amplifiers use a circuit configuration of this type.

2-72. In the CB configuration, the input signal is applied to the emitter, the output is taken from the collector, and the base is the element common to input and output. Since the input is applied to the emitter, it causes the emitter-base junction to react in the same manner as it did in the CE circuit. For example, an input that aids the bias will increase transistor current and one that opposes the bias will decrease transistor current.

2-73. Unlike the CE circuit, the input and output signals in the CB circuit are in phase. To illustrate this point, assume the input to the PNP version of the CB circuit in Figure 2-17, view (B) is positive. The signal adds to the forward bias, since it is applied to the emitter, causing the collector current to increase. This increase in I_C results in a greater voltage drop across the load resistor R_L (not shown), thereby lowering the collector voltage V_C. The collector voltage, in becoming less negative, is swinging in a positive direction and is therefore in phase with the incoming positive signal.

2-74. The current gain in the CB circuit is calculated in a method similar to that of the CE except that the input current is I_E not I_B and the term ALPHA (α) is used in place of beta for gain. Alpha is the relationship of collector current (output current) to emitter current (input current). Alpha is calculated using the formula:

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

For example, if the input current (I_E) in a CB changes from 1 mA to 3 mA and the output current (I_C) changes from 1 mA to 2.8 mA, then the current gain *(a)* would be 0.90 (see below formula):

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

$$= \frac{1.8 \text{ x } 10^{-3}}{2 \text{ x } 10^{-3}}$$

$$= 0.90$$

This is a current gain of less than 1.

2-75. Since part of the emitter current flows into the base and does not appear as collector current, then collector current will always be less than the emitter current that causes it. Remember, $I_E = I_B + I_C$, therefore, ALPHA is ALWAYS LESS THAN ONE FOR A CB CONFIGURATION.

2-76. Another term for "α" is h_{fb}. These terms (α and h_{fb}) are equivalent and may be used interchangeably. The meaning for the term h_{fb} is derived in the same manner as the term h_{fe} mentioned earlier, except that the last letter "*e*" has been replaced with "*b*" to stand for CB configuration.

2-77. Many transistor manuals and data sheets only list transistor current gain characteristics in terms of β or h_{fe}. To find alpha (α) when given beta (β), use the following formula to convert β to *a* for use with the CB configuration:

$$\alpha = \frac{\beta}{\beta + 1}$$

To calculate the other gains (voltage and power) in the CB configuration when the current gain *(a)* is known, follow the procedures described earlier under the CE section.

Common Collector

2-78. The CC configuration (see Figure 2-17, view (C)) is used mostly for impedance matching. It is also used as a current driver, due to its substantial current gain. It is particularly useful in switching circuitry, since it has the ability to pass signals in either direction (bilateral operation).

2-79. In the CC circuit, the input signal is applied to the base, the output is taken from the emitter, and the collector is the element common to input and output. The CC is equivalent to the electron-tube cathode follower. Both have high input and low output resistance. The input resistance for the CC ranges from 2 kilohms to 500 kilohms and the

output resistance varies from 50 ohms to 1,500 ohms. The current gain is higher than that in the CE, but it has a lower power gain than either the CB or CE. Like the CB, the output signal from the CC is in phase with the input signal. The CC is also referred to as an emitter-follower because the output developed on the emitter follows the input signal applied to the base.

2-80. Transistor action in the CC is similar to the operation explained for the CB, except that the current gain is not based on the emitter-to-collector current ratio, alpha (α). Instead, it is based on the emitter-to-base current ratio called GAMMA (γ), because the output is taken off the emitter. Since a small change in base current controls a large change in emitter current, it is still possible to obtain high current gain in the CC. However, since the emitter current gain is offset by the low output resistance, the voltage gain is always less than 1 (unity), exactly as in the electron-tube cathode follower.

2-81. The CC current gain, gamma (γ), is defined as follows:

$$\gamma = \frac{I_E}{I_B}$$

and is related to collector-to-base current gain, beta (β), of the CE circuit by the formula:

$$\gamma = \beta + 1$$

2-82. Since a given transistor may be connected in any of three basic configurations, then there is a definite relationship, as pointed out earlier, between alpha, beta, and gamma. These relationships are listed again for your convenience:

$$\text{Alpha}\,(\alpha) = \frac{\beta}{\beta + 1}$$

$$\text{Beta}\,(\beta) = \frac{\alpha}{1 - \alpha}$$

$$\text{Gamma}\,(\gamma) = \beta + 1$$

2-83. Take, for example, a transistor that is listed on a manufacturer's data sheet as having an alpha of 0.90, but we want to use it in a CE configuration. This means we must find beta. The calculations are as follows:

$$\beta = \frac{\alpha}{1 - \alpha} = \frac{0.90}{1 - 0.90} = \frac{0.90}{0.1} = 9$$

Therefore, a change in base current in this transistor will produce a change in collector current that will be 9 times larger. If we want to use this same transistor in a CC, we can find gamma by using the following formula:

$$\text{Gamma} = \beta + 1 = 9 + 1 = 10$$

To summarize the properties of the three transistor configurations, a comparison chart is provided in Table 2-1 for your convenience.

Table 2-1. Transistor Configuration Comparison Chart

AMPLIFIER TYPE	COMMON BASE	COMMON EMITTER	COMMON COLLECTOR
INPUT/OUTPUT PHASE RELATIONSHIP	0^o	180^o	0^o
VOLTAGE GAIN	HIGH	MEDIUM	LOW
CURRENT GAIN	LOW (α)	MEDIUM (β)	HIGH (γ)
POWER GAIN	LOW	HIGH	MEDIUM
INPUT RESISTANCE	LOW	MEDIUM	HIGH
OUTPUT RESISTANCE	HIGH	MEDIUM	LOW

2-84. Now that we have analyzed the basic transistor amplifier in terms of bias, class of operation, and circuit configuration, let us apply what has been covered to Figure 2-14. For your convenience, Figure 2-19 is a reproduction of Figure 2-14.

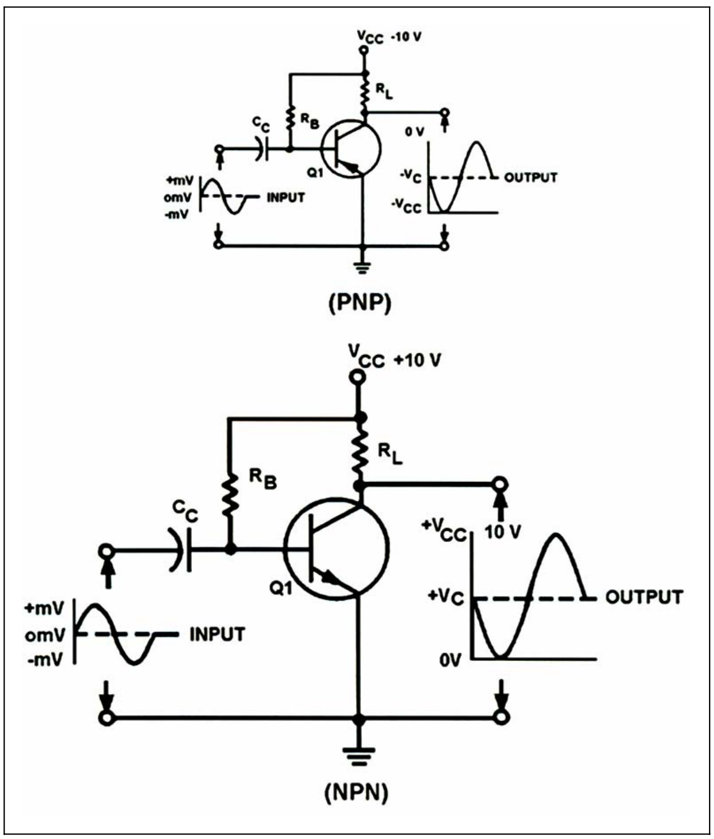


Figure 2-19. Reproduction of Figure 2-14

2-85. Figure 2-19 is not just the basic transistor amplifier as shown in Figure 2-14, but a class A amplifier configured as a CE using fixed bias. From Figure 2-19 you should be able to conclude the following about the amplifier:

- It is thermally unstable because of its fixed bias.
- It has low efficiency but good fidelity because of its class A operation.
- It has good voltage, current, and power gain because it is configured as a CE.

The type of bias, class of operation, and circuit configuration are all clues to the function and possible application of the amplifier.

TRANSISTOR SPECIFICATIONS

2-86. Transistors, like electron tubes, are available in a large variety of shapes and sizes and each with its own unique characteristics. The characteristics for each of these transistors are usually presented on SPECIFICATION SHEETS or they may be included in transistor manuals. Although many properties of a transistor could be specified on these sheets, manufacturers list only some of them. The specifications listed vary with different manufacturers, the type of transistor, and the application of the transistor. The specifications usually cover the following items.

TRANSISTOR DESCRIPTION

2-87. A general description of the transistor, includes the following:

- The kind of transistor. This covers the material used (such as germanium or silicon, the type of transistor [NPN or PNP], and the construction of the transistor [whether alloy junction, grown, diffused junction, and so forth]).
- Some of the common applications for the transistor (such as audio amplifier, oscillator, RF amplifier, and so forth).
- General sales features (such as size and packaging [mechanical data]).

TRANSISTOR ABSOLUTE MAXIMUM RATINGS

2-88. The "Absolute Maximum Ratings" of the transistor are the direct voltage and current values that if exceeded in operation may result in transistor failure. Maximum ratings usually include collector-to-base voltage, emitter-to-base voltage, collector current, emitter current, and collector power dissipation.

TRANSISTOR TYPICAL OPERATING VALUES

2-89. These values are presented only as a guide. The values vary widely and are dependent upon operating voltages and also upon which element is common in the circuit. The values listed may include collector-emitter voltage, collector current, input resistance, load resistance, current-transfer ratio (another name for alpha or beta), and collector cutoff current, which is leakage current from collector to base when no emitter current is applied. Transistor characteristic curves may also be included. A transistor characteristic curve is a graph plotting the relationship between currents and voltages in a circuit. More than one curve on a graph is called a "family of curves."

TRANSISTOR IDENTIFICATION

2-90. You can identify transistors by a JAN designation printed directly on the case of the transistor. The marking scheme (shown below) and explained earlier for diodes is also used for transistor ID. The first number indicates the number of junctions. The letter "N" following the first number tells us that the component is a semiconductor. The 2- or 3-digit number following the N is the manufacturer's ID number. If the last number is followed by a letter, it indicates a later, improved version of the device. For example, a semiconductor designated as type 2N 130A signifies a three-element transistor of semiconductor material that is an improved version of type 130.

2	N	130	A
Number of Junctions (Transistor)	Semiconductor	Identification Number	First Modification

2-91. You may also find other markings on transistors that do not relate to the JAN marking system. These markings are manufacturers IDs and may not conform to a standardized system. If in doubt, always replace a transistor with one having identical markings. To ensure that an identical replacement or a correct substitute is used, consult an equipment or transistor manual for specifications on the transistor.

TRANSISTOR MAINTENANCE

2-92. Transistors, unlike electron tubes, are very rugged and are expected to be relatively trouble free. Encapsulation and conformal coating techniques now in use promise extremely long life expectancies. In theory, a transistor should last indefinitely. However, if transistors are subjected to current overloads, the junctions will be damaged or even destroyed. The application of excessively high operating voltages can also damage or destroy the junctions through arc-over or excessive reverse currents. One of the greatest dangers to the transistor is heat, which will cause excessive current flow and eventual destruction of the transistor.

2-93. To determine if a transistor is good or bad, you can check it with an ohmmeter or a transistor tester. In many cases you can substitute a transistor known to be good for one that is questionable to determine the condition of a suspected transistor. This method of testing is highly accurate and sometimes the quickest. However, use this method only after you are sure that there are no circuit defects that might damage the replacement transistor. If more than one defective transistor is found in the equipment where the trouble has been localized, this testing method becomes cumbersome, as several transistors may have to be replaced before the trouble is corrected. To determine which stages failed and which transistors are not defective, all the removed transistors must be tested. You can perform this test by using a standard Army ohmmeter, a transistor tester, or by observing whether the equipment operates correctly as each of the removed transistors is reinserted into the equipment. A word of caution, avoid randomly substituting transistors in critical circuits. When transistors are soldered into equipment, substitution is not practicable; it is generally desirable to test these transistors in their circuits.

PRECAUTIONS

2-94. Transistors, although generally more rugged mechanically than electron tubes, are subject to damage by electrical overloads, heat humidity, and radiation. Damage of this

nature often occurs during transistor servicing by applying the incorrect polarity voltage to the collector circuit or excessive voltage to the input circuit. Careless soldering techniques that overheat the transistor have also been known to cause considerable damage.

2-95. One of the most frequent causes of damage to a transistor is the electrostatic discharge from the human body when the device is handled. To avoid such damage before starting repairs, discharge the static electricity from your body to the chassis containing the transistor. You can do this by simply touching the chassis. Therefore, the electricity will be transferred from your body to the chassis before you handle the transistor.

2-96. There are a number of ways to prevent transistor damage and avoid electrical shock. Observe the following precautions when you are working with transistorized equipment.

PRECAUTIONS

- Check test equipment and soldering irons to ensure that there is no leakage current from the power source. If leakage current is detected, isolation transformers should be used.
- Always connect a ground between test equipment and circuit before attempting to inject or monitor a signal.
- Ensure test voltages do not exceed maximum allowable voltage for circuit components and transistors.
- NEVER connect test equipment outputs directly to a transistor circuit.
- Ohmmeter ranges, which require a current of more than one milliampere in the test circuit, should not be used for testing transistors.
- DO NOT use battery eliminators to furnish power for transistor equipment because they have poor voltage regulation and, possibly, high-ripple voltage.
- When soldered connections are required, keep the heat applied to the transistor leads to a minimum by using a low-wattage soldering iron and heat shunts (such as long-nose pliers).
- NEVER pry transistors from printed circuit boards when it becomes necessary to replace them.
- Check all circuits for defects before replacing a transistor.
- Remove power from the equipment before replacing a transistor.
- Using conventional test probes on equipment with closely spaced parts often causes accidental shorts between adjacent terminals. These shorts rarely cause damage to an electron tube but may ruin a transistor. To prevent these shorts, the probes can be covered with insulation, except for a very short length of the tips.

TRANSISTOR LEAD IDENTIFICATION

2-97. Transistor lead identification plays an important part in transistor maintenance. Before a transistor can be tested or replaced, its leads or terminals must be identified. Since there is no standard method of identifying transistor leads, it is quite possible to mistake one lead for another. Therefore, when you are replacing a transistor, you should pay close attention to how the transistor is mounted. Pay attention to those transistors that are soldered in, so that you do not make a mistake when you are installing the new transistor. When you are testing or replacing a transistor, if you have any doubts about which lead is

which, consult the equipment manual or a transistor manual that shows the specifications for the transistor being used.

2-98. There are, however, some typical lead identification schemes that will be very helpful in transistor troubleshooting. Figure 2-20 shows these schemes. In the case of the oval shaped transistors shown in view (A), the collector lead is identified by a wide space between it and the base lead. The lead farthest from the collector, in line, is the emitter lead. When the leads are evenly spaced and in line, as shown in view (B), a colored dot, usually red, indicates the collector. If the transistor is round, as in view (C), a red line indicates the collector, and the emitter lead is the shortest lead. In view (D) the leads are in a triangular arrangement that is offset from the center of the transistor. The lead opposite the blank quadrant in this scheme is the base lead. When viewed from the bottom, the collector is the first lead clockwise from the base. The leads in view (E) are arranged in the same manner as those in view (D) except that a tap is used to identify the leads. When viewed from the bottom in a clockwise direction, the first lead following the tab is the emitter, followed by the base and collector.

2-99. In a conventional power transistor as shown in Figure 2-20, views (F) and (G), the collector lead is usually connected to the mounting base. For further identification, the base lead in view (F) is covered with green sleeving. You can identify the leads in view (G) by viewing the transistor from the bottom in a clockwise direction (with mounting holes occupying 3 o'clock and 9 o'clock positions). The emitter lead will be either at the 5 o'clock or 11 o'clock position. The other lead is the base lead.

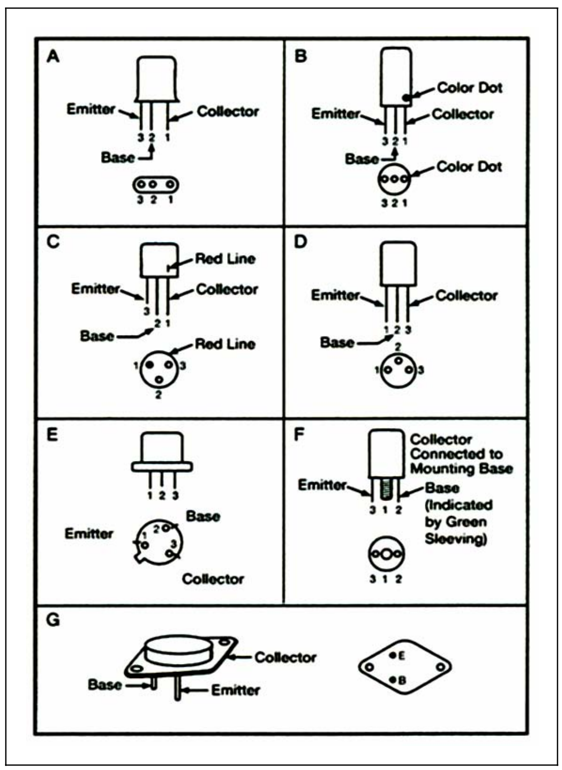


Figure 2-20. Transistor Lead Identification

TRANSISTOR TESTING

2-100. There are several different ways of testing transistors. They can be tested while in the circuit, by the substitution method mentioned, or with a transistor tester or ohmmeter.

Transistor testers are nothing more than the solid state equivalent of electron-tube testers (although they do not operate on the same principle). With most transistor testers, it is possible to test the transistor in or out of the circuit. It is impossible to cover all the different types of transistor testers. Since each tester comes with its own operator's manual, we will discuss the most frequently used tester, the ohmmeter, for testing transistors.

Testing Transistors With an Ohmmeter

2-101. There are four basic tests used for practical troubleshooting of transistors. These tests check for gain, leakage, breakdown, and switching time. However, for maintenance and repair, it is usually not necessary to check all of these parameters. A check of two or three parameters is usually sufficient to determine whether a transistor needs to be replaced. Two of the most important parameters used for testing are gain and leakage. The following describes the tests (using the ohmmeter) to check for transistor gain and leakage.

TRANSISTOR GAIN TEST - A basic transistor gain test can be made using an ohmmeter and a simple test circuit. The test circuit can be made with just a couple of resistors and a switch (see Figure 2-21). The principle behind the test lies in the fact that little or no current will flow in a transistor between emitter and collector until the emitter-base junction is forward biased. The only precaution you should observe is with the ohmmeter. Any internal battery may be used in the meter provided that it does not exceed the maximum collector-emitter breakdown voltage. With the switch in the open position (see Figure 2-21), no voltage is applied to the PNP transistor's base, and the emitter-base junction is not forward biased. Therefore, the ohmmeter should read a high resistance, as indicated on the meter. When the switch is closed, the emitter-base circuit is forward biased by the voltage across R1 and R2. Current now flows in the emitter-collector circuit that causes a lower resistance reading on the ohmmeter. A 10-to-l resistance ratio in this test between meter readings indicates a normal gain for an audio-frequency transistor. To test an NPN transistor using this circuit, simply reverse the ohmmeter leads and carry out the procedure described earlier.

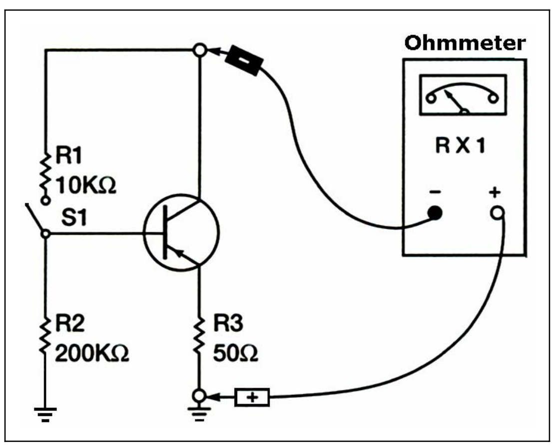


Figure 2-21. Testing a Transistor's Gain with an Ohmmeter

TRANSISTOR LEAKAGE TEST – Use an ohmmeter to test a transistor for leakage (an undesirable flow of current). Perform this test by measuring the base-emitter, base-collector, and collector-emitter forward and reverse resistances. For simplicity, consider the transistor under test in each view of Figure 2-22 as two diodes connected back to back. Therefore, each diode will have a low-forward resistance and a high-reverse resistance. By

measuring these resistances with an ohmmeter as shown in the figure, you can determine if the transistor is leaking current through its junctions. When making these measurements, avoid using the R x 1 scale on the meter or a meter with a high internal battery voltage. Either of these conditions can damage a low-power transistor. Now consider the possible transistor problems (see Table 2-2) that could exist if the indicated readings in Figure 2-22 are not obtained. Figure 2-22 shows a PNP transistor. If you need to test an NPN transistor for leakage, the procedure is identical to that used for testing the PNP except the readings obtained are reversed.

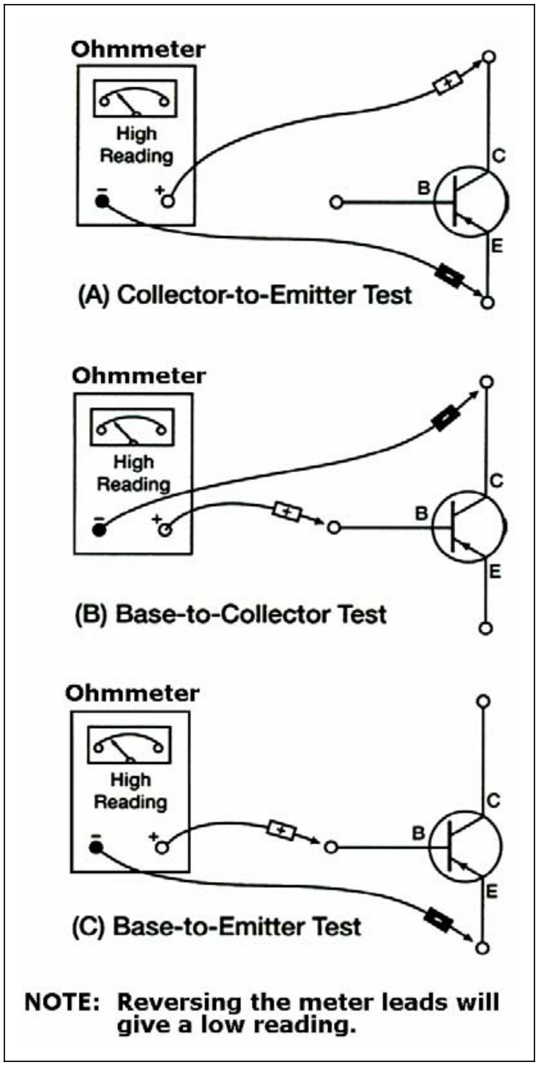


Figure 2-22. Testing a Transistor's Leakage with an Ohmmeter

Table 2-2. Possible Transistor Problems

RESISTANCE READINGS		PROBLEMS
FORWARD	REVERSE	The transistor is:
	LOW (NOT SHORTED)	LEAKING
LOW (SHORTED)	LOW (SHORTED)	SHORTED
HIGH SAME (NEARLY EQUAL)	HIGH SAME (NEARLY EQUAL)	OPEN DEFECTIVE

2-102. When testing PNP or NPN transistors, you should remember that the actual resistance values depend on the ohmmeter scale and the battery voltage. Typical forward and reverse resistances are insignificant. The best indicator for showing whether a transistor is good or bad is the ratio of forward-to-reverse resistance. If the transistor you are testing shows a ratio of at least 30 to 1, it is probably good. Many transistors show ratios of 100 to l or greater.

MICROELECTRONICS

2-103. Up to now the various semiconductors, resistors, capacitors, and so on have been considered as separately packaged components, called DISCRETE COMPONENTS. We will now look at some of the more complex devices that contain complete circuits packaged as a single component. These devices are referred to as INTEGRATED CIRCUITS and the broad term used to describe the use of these devices to miniaturize electronic equipment is called MICROELECTRONICS.

2-104. With the advent of the transistor and the demand by the military for smaller equipment, design engineers set out to miniaturize electronic equipment. At first, their efforts were frustrated because most of the other components in a circuit such as resistors, capacitors, and coils were larger than the transistor. Soon these other circuit components were miniaturized, thereby pushing ahead the development of smaller electronic equipment. Along with miniature resistors, capacitors, and other circuit elements, the production of components that were actually smaller than the space required for the interconnecting wiring and cabling became possible. The next step in the research process was to eliminate these bulky wiring components. This was accomplished with the PCB.

2-105. A PCB is a flat, insulating surface on which printed wiring and miniaturized components are connected in a predetermined design and attached to a CB. Figure 2-23 shows a typical PCB. Notice that various components are connected to the board and the printed wiring is on the reverse side. With this technique, all interconnecting wiring in a piece of equipment (except for the highest power leads and cabling) is reduced to lines of conducting material (copper, silver, aluminum, or gold) deposited directly on the surface of an insulating "circuit board." Since PCBs are readily adapted as plug-in units, the

elimination of terminal boards, fittings, tie points, and wires, results in a substantial reduction in the overall size of electronic equipment.

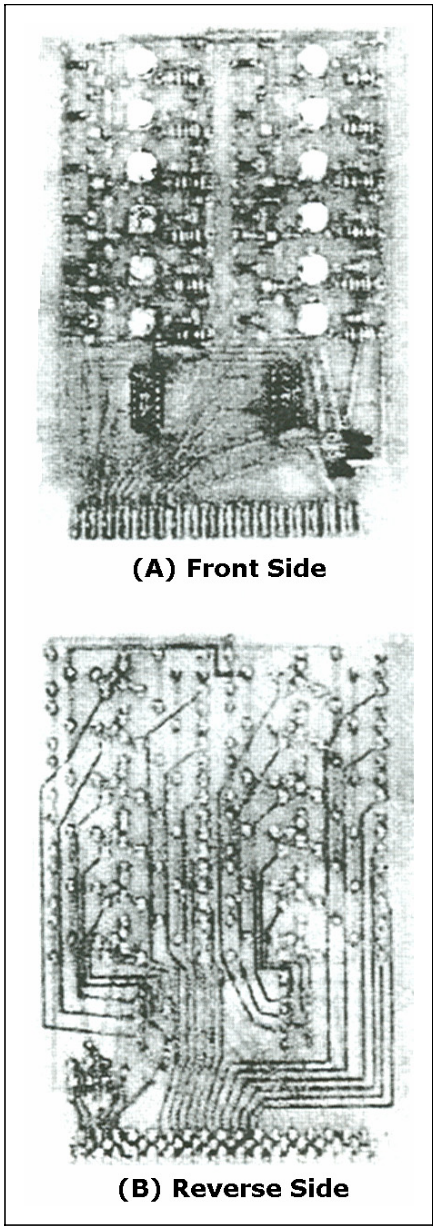


Figure 2-23. Typical Printed Circuit Board

2-106. After the PCBs were perfected, efforts to miniaturize electronic equipment were then shifted to assembly techniques, which led to MODULAR CIRCUITRY. In this technique, PCBs are stacked and connected together to form a module. This increases the packaging density of circuit components and results in a considerable reduction in the size of electronic equipment. Since the module can be designed to perform any electronic function, it is also a very versatile unit. However, the drawback to this approach was that the modules required a considerable number of connections that took up too much space and increased costs. Tests also showed the reliability was adversely affected by the increase in the number of connections.

2-107. A new technique was required to improve reliability and further increase packaging density. The solution was INTEGRATED CIRCUITS. An IC is a device that integrates (combines) both active components (transistors, diodes, and so on) and passive components (resistors, capacitors, and so on) of a complete electronic circuit in a single chip (a tiny slice or wafer of semiconductor crystal or insulator).

2-108. ICs have almost eliminated the use of individual electronic components (resistors, capacitors, transistors, and so on) as the building blocks of electronic circuits. Instead, tiny CHIPS have been developed whose functions are not that of a single part, but of dozens of transistors, resistors, capacitors, and other electronic elements, all interconnected to perform the task of a complex circuit. Often these make up a number of complete conventional circuit stages, such as a multistage amplifier (in one extremely small component). These chips are frequently mounted on a plastic card called an integrated circuit board (see Figure 2-24), which plugs into an electronic unit.

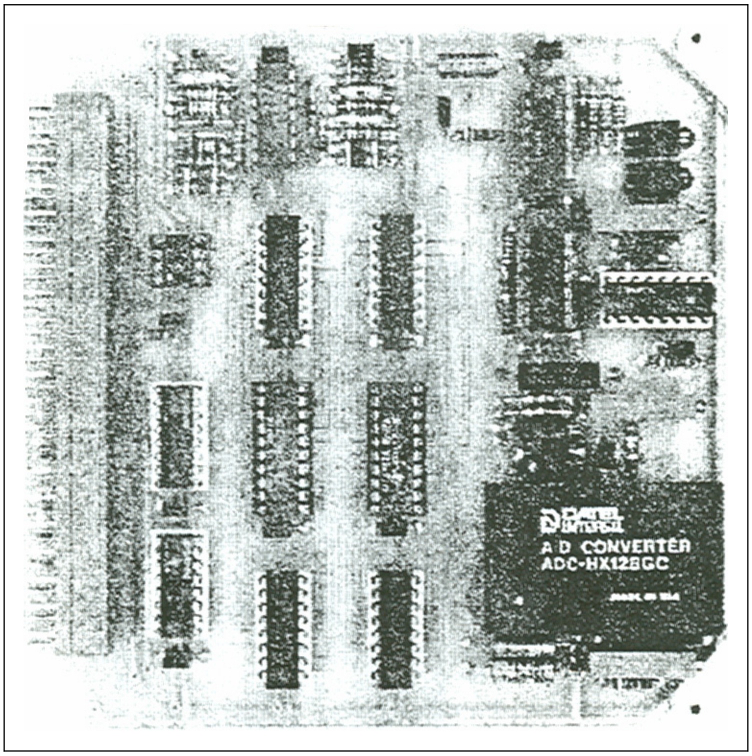


Figure 2-24. Typical ICB

2-109. ICs have several advantages over conventionally wired circuits of discrete components. These advantages include the following:

- A drastic reduction in size and weight.
- A large increase in reliability.
- Lower cost.
- Possible improvement in circuit performance.

However, ICs are made up of parts so closely associated with one another that repair becomes almost impossible. In case of trouble, the entire circuit is replaced as a single component.

2-110. There are two basic general classifications of ICs (HYBRID and MONOLITHIC). In the monolithic IC, all elements (such as resistors, transistors, and so forth) associated with the circuit are fabricated inseparably within a continuous piece of material (usually silicon) called the SUBSTRATE. The monolithic IC is made very much like a single transistor. While one part of the crystal is being doped to form a transistor, other parts of the crystal are being acted upon to form the associated resistors and capacitors. Therefore, all the elements of the complete circuit are created in the crystal by the same processes and in the same time required to make a single transistor. This produces a considerable cost savings over the same circuit made with discrete components by lowering assembly costs.

2-111. Hybrid ICs are constructed somewhat differently from the monolithic devices. The PASSIVE components (resistors and capacitors) are deposited onto a substrate (foundation) made of glass, ceramic, or other insulating material. Then the ACTIVE components (diodes and transistors) are attached to the substrate and connected to the passive circuit components on the substrate using very fine (.001 inch) wire. The term "hybrid" refers to the fact that different processes are used to form the passive and active components of the device.

2-112. Hybrid circuits are of two general types (thin film and thick film). "Thin" and "thick" film refers to the relative thickness of the deposited material used to form the resistors and other passive components. Thick film devices are capable of dissipating more power but are somewhat more bulky.

2-113. ICs are being used in an ever-increasing variety of applications. Small size and weight and high reliability make them ideally suited for use in airborne equipment, missile systems, computers, spacecraft, and portable equipment. They are often easily recognized because of the unusual packages that contain the IC. Figure 2-25 shows a typical packaging sequence. These tiny packages protect and help dissipate heat generated in the device. One of these packages may contain one or several stages, often having several hundred components. Figure 2-26 shows some of the most common package styles.

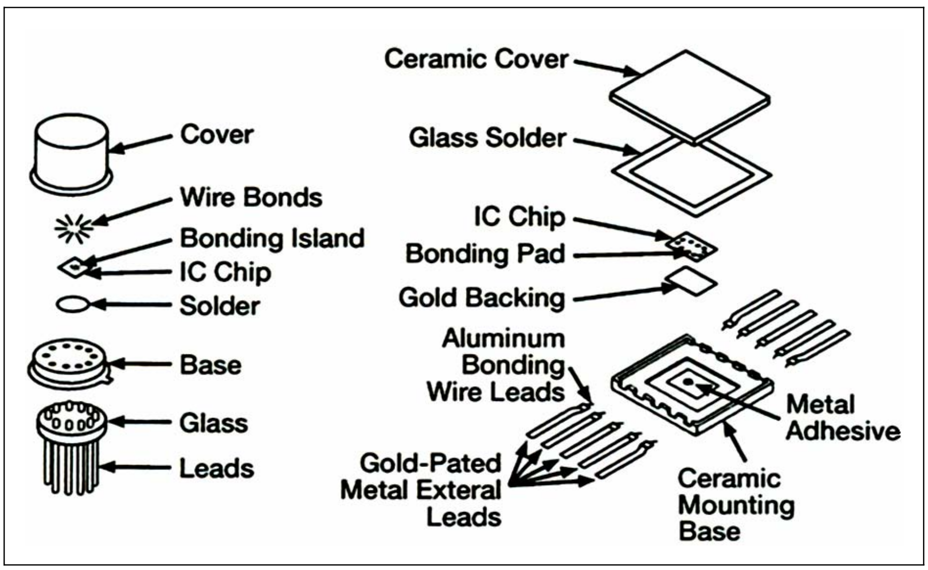


Figure 2-25. Typical IC Packaging Sequence

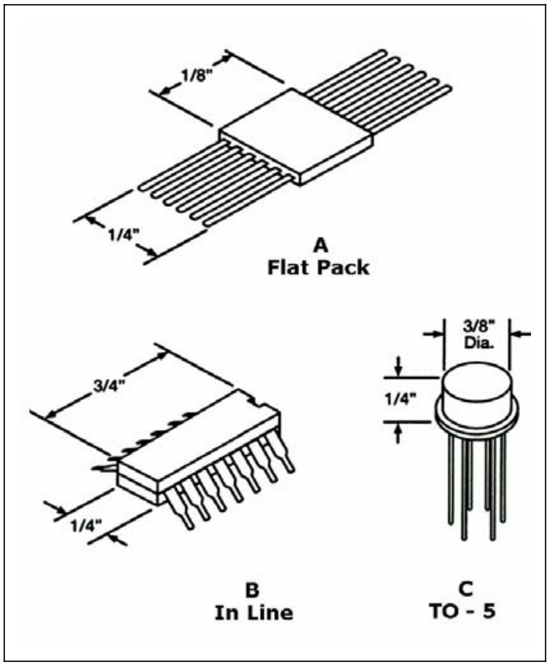
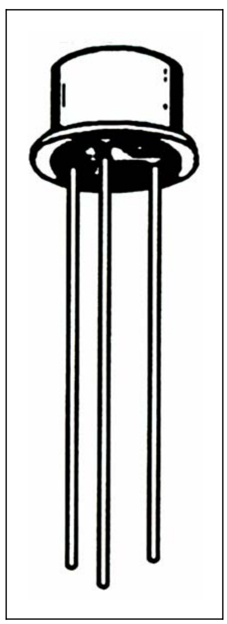


Figure 2-26. Common IC Packaging Styles

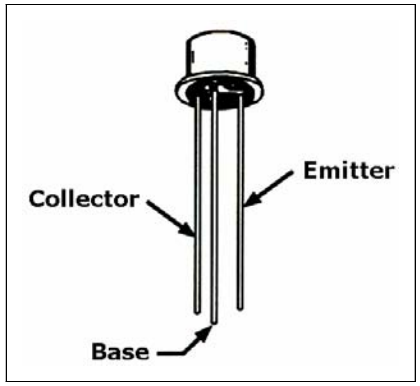
SUMMARY

2-114. Now that we have completed this chapter, the following is a short review of the more important points. Answer the check-on-learning questions, found after the summary, to determine how much you have learned from this chapter.

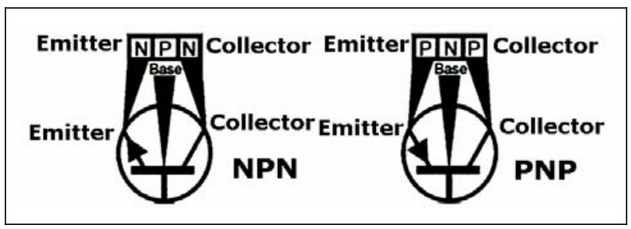
TRANSISTOR - a solid state device that amplifies by controlling the flow of current carriers through its semiconductor materials.



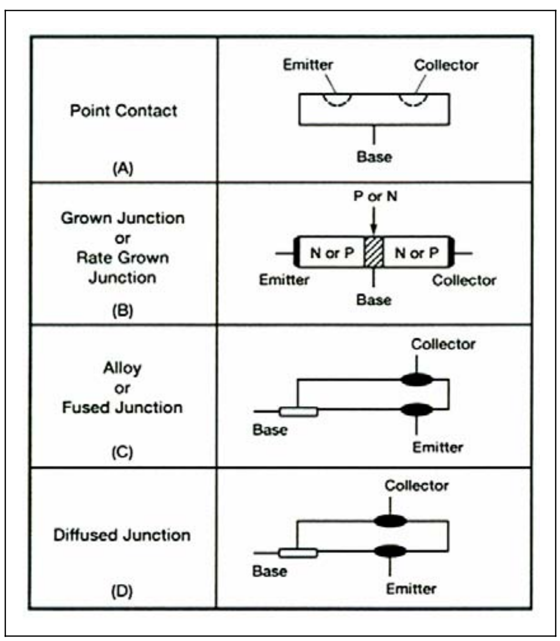
THREE ELEMENTS OF A TRANSISTOR - consists of the EMITTER, which gives off current carriers; the BASE, which controls the carriers; and the COLLECTOR, which collects the carriers.



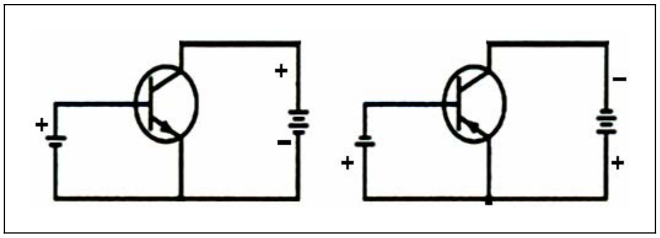
TWO BASIC TYPES OF TRANSISTORS - are the NPN and PNP. The only difference in symbolism between the two transistors is the direction of the arrow on the emitter. If the arrow points in, it is a PNP transistor and if it points outward, it is an NPN transistor.



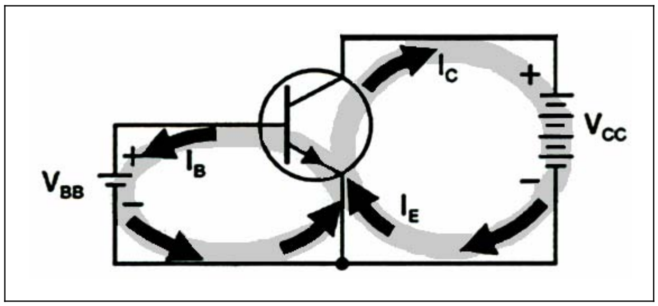
FOUR TRANSISTOR MANUFACTURING PROCESSES - are the (A) point contact, (B) grown or rate-grown junction, (C) alloy or fused junction, and (D) diffused junction.



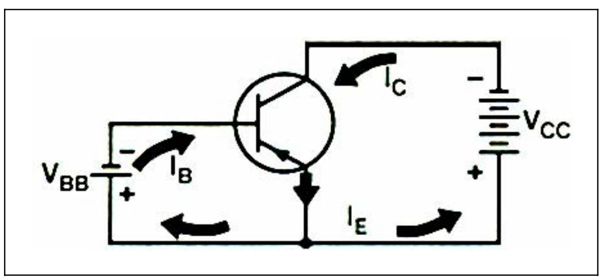
PROPER BIASING OF A TRANSISTOR **-** enables the transistor to be used as an amplifier. To function in this capacity, the emitter-to-base junction of the transistor is forward biased, while the base-to-collector junction is reverse biased.



NPN TRANSISTOR OPERATION **-** basically is the action of a relatively small emitter-base bias voltage controlling a relatively large emitter-to-collector current.



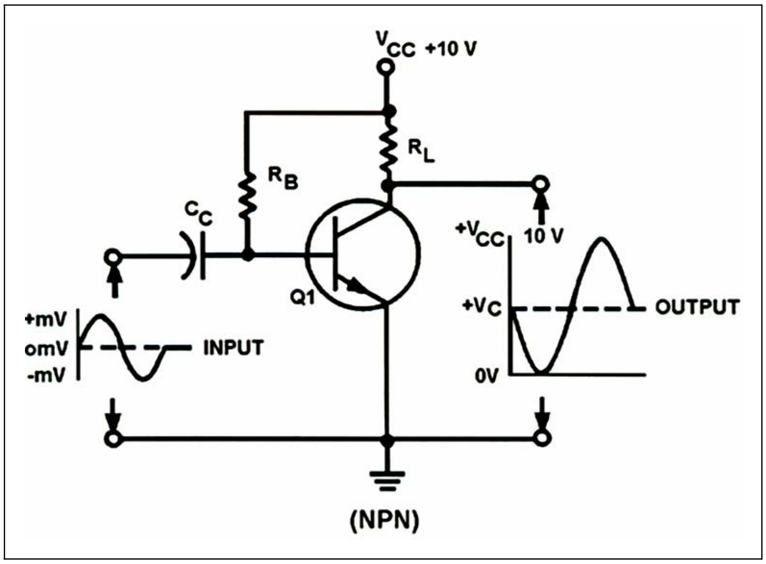
PNP TRANSISTOR OPERATION **-** essentially the same as the NPN operation except the majority current carriers are holes and the bias batteries are reversed.



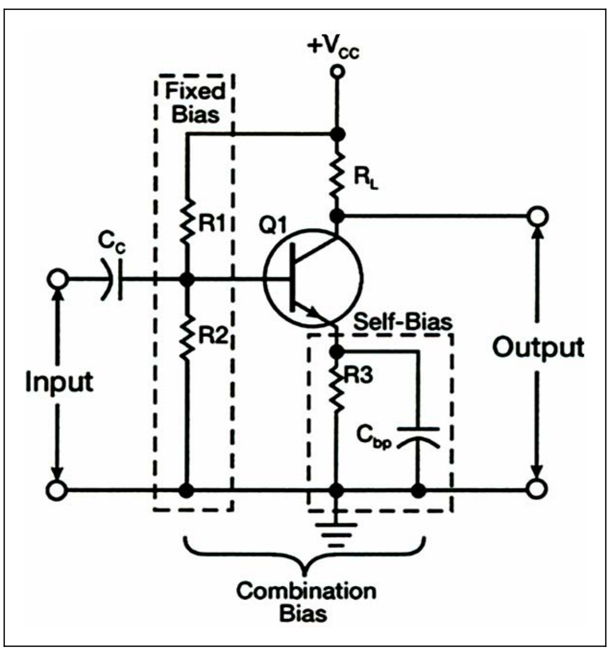
AMPLIFICATION **-** the process of increasing the strength of a signal.

AMPLIFIER **-** the device that provides amplification without appreciably altering the original signal.

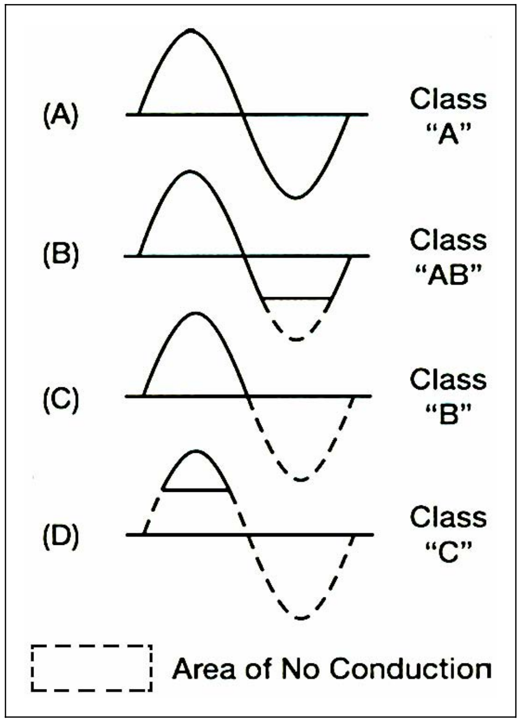
BASIC TRANSISTOR AMPLIFIER **-** amplifies by producing a large change in collector current for a small change in base current. This action results in voltage amplification because the load resistor placed in series with the collector reacts to these large changes in collector current that, in turn, results in large variations in the output voltage.



THREE TYPES OF BIAS **-** used to properly bias a transistor are base-current bias (fixed bias), self-bias, and combination bias. Combination bias is the one most widely used because it improves circuit stability and at the same time overcomes some of the disadvantages of base-current bias and self-bias.



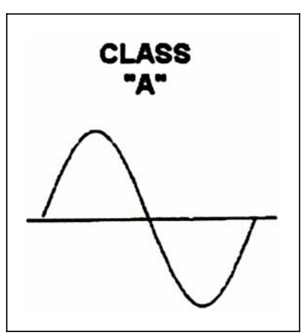
CLASSES OF AMPLIFIER OPERATION **-** determined by the portion of the input signal for which there is an output. There are four classes of amplifier operations: class A, class AB, class B, and class C.



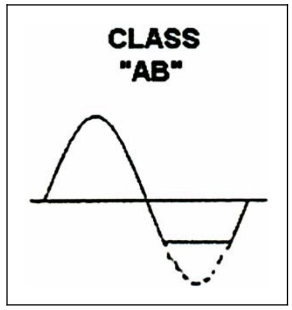
CUTOFF **-** occurs when the base-to-emitter bias prevents current from flowing in the emitter circuit. For example, in the PNP transistor, if the base becomes positive with respect to the emitter, holes are repelled at the emitter-base junction. This prevents current from flowing in the collector circuit.

SATURATION **-** occurs in a PNP transistor when the base becomes so negative, with respect to the emitter, that changes in the signal are not reflected in collector-current flow.

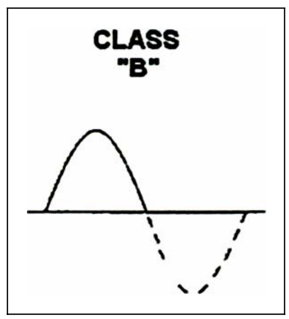
CLASS A AMPLIFIERS **-** biased so that variations in input signal polarities occur within the limits of cutoff and saturation. Biasing an amplifier in this manner allows collector current to flow during the complete cycle (360 degrees) of the input signal, thereby providing an output that is a replica of the input but 180 degrees out of phase. Class A operated amplifiers are used as audio and RF amplifiers in radio, radar, and sound systems.



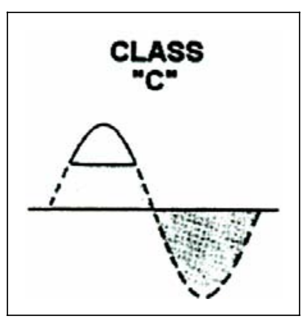
CLASS AB AMPLIFIERS - biased so that collector current is zero (cutoff) for a portion of one alternation of the input signal. Therefore, collector current will flow for more than 180 degrees but less than 360 degrees of the input signal. The class AB amplifier is commonly used as a push-pull amplifier to overcome a side effect of class B operations.



CLASS B AMPLIFIERS - biased so that collector current is cut off during one-half of the input signal. So, for a class B operation, collector current will flow for approximately 180 degrees (halt) of the input signal. The class B operated amplifier is used as an audio amplifier and sometimes as the driver- and power-amplifier stage of transmitters.

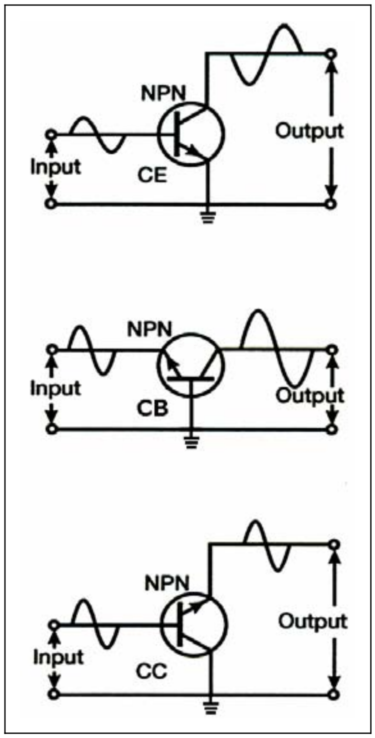


CLASS C AMPLIFIERS - biased so that collector current flows for less than one-half cycle of the input signal. The class C operated amplifier is used as a RF amplifier in transmitters.

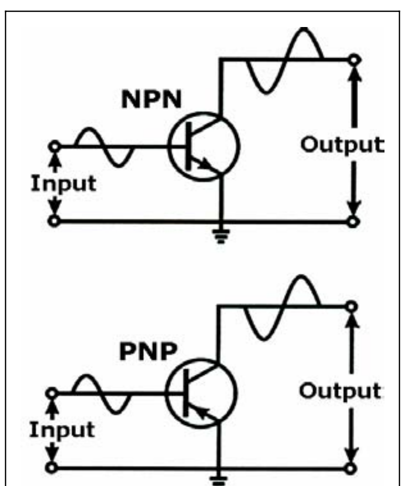


FIDELITY AND EFFICIENCY - two terms used in conjunction with amplifiers. Fidelity is the faithful reproduction of a signal while efficiency is the ratio of output signal power compared to the total input power. The class A amplifier has the highest degree of fidelity, but the class C amplifier has the highest efficiency.

TRANSISTOR CONFIGURATION - the particular way a transistor is connected in a circuit. A transistor may be connected in any one of three different configurations: common emitter, common base, and common collector.

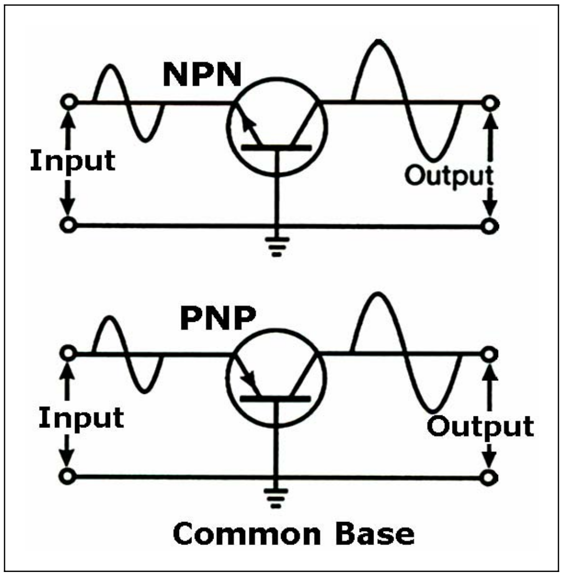


COMMON EMITTER CONFIGURATION - the most frequently used configuration in practical amplifier circuits, since it provides good voltage, current, and power gain. The input to the CE is applied to the base-emitter circuit and the output is taken from the collector-emitter circuit, making the emitter the element "common" to input and output. The CE is set apart from the other configurations, because it is the only configuration that provides a phase reversal between input and output signals.

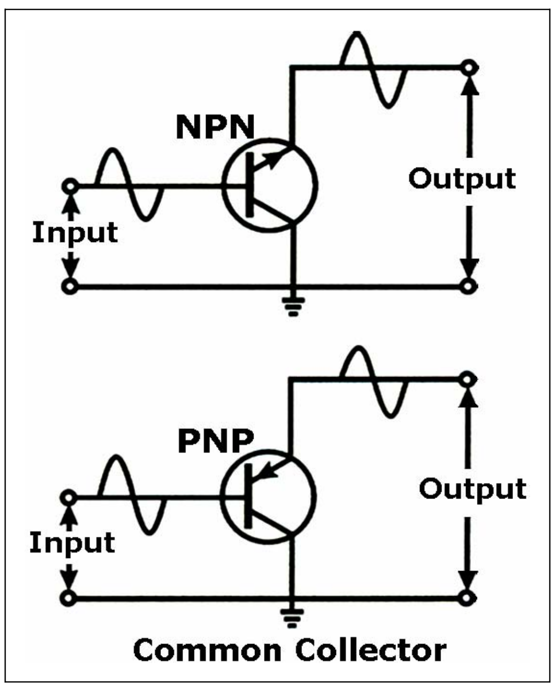


Common Emitter

COMMON BASE CONFIGURATION - mainly used for impedance matching, since it has a low input resistance and a high output resistance. It also has a current gain of less than 1. In the CB, the input is applied to the emitter, the output is taken from the collector, and the base is the element common to input and output.



COMMON COLLECTOR CONFIGURATION - used as a current driver for impedance matching and is particularly useful in switching circuits. The CC is also referred to as an emitter-follower and is equivalent to the electron-tube cathode follower. Both have high input impedance and low output impedance. In the CC, the input is applied to the base, the output is taken from the emitter, and the collector is the element common to input and output.



GAIN **-** term used to describe the amplification capabilities of an amplifier. It is basically a ratio of output to input. The current gain for the three transistor configurations (CB, CE, and CC) are ALPHA (α), BETA (β), and GAMMA (γ), respectively.

$$\alpha = \frac{\Delta IC}{\Delta IE}$$

$$\beta = \frac{\Delta IC}{IB}$$

$$\gamma = \frac{\Delta IE}{\Delta IB}$$

TRANSISTOR AMPLIFIER COMPARISON CHART **-** gives a rundown of the different properties of the three configurations.

Amplifier Type	Common Base	Common Emitter	Common Collector
Input/Output Phase Relationship	0°	180°	0°
Voltage Gain	High (α)	Medium (β)	Low (γ)
Current Gain	Low	Medium	High
Input Resistance	Low	Medium	High
Output Resistance	High	Medium	Low

TRANSISTOR CHARACTERISTICS **-** usually presented on specification sheets. These sheets usually cover the following items:

- The kind of transistor.
- The absolute maximum ratings of the transistor.
- The typical operating values of the transistor.
- Additional engineering/design information.

TRANSISTOR IDENTIFICATION – identified by a JAN designation printed directly on the case of the transistor. If in doubt about a transistor's markings, always replace a transistor with one having identical markings, or consult an equipment or transistor manual to ensure that an identical replacement or substitute is used.

2
Number of Junctions (Transistors)

N
Semiconductor

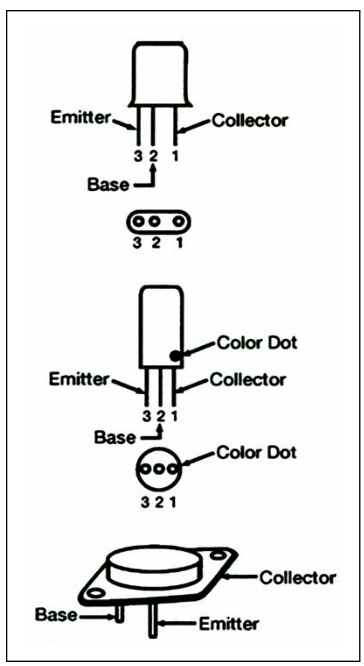
130
Identification Number

A
First Modification

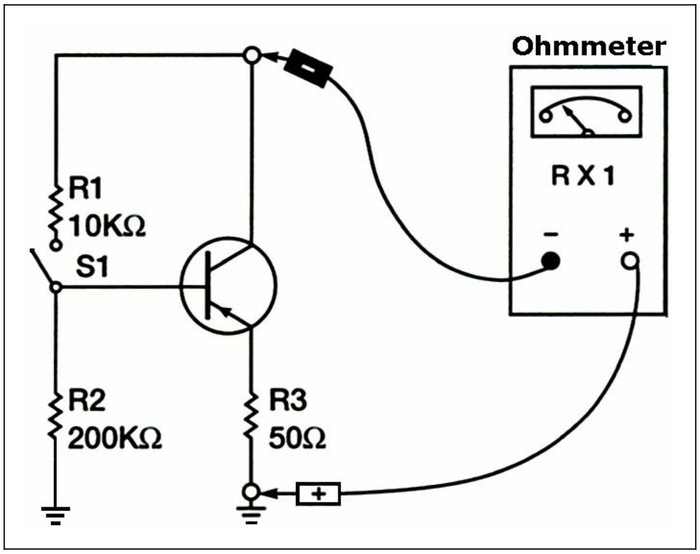
TESTING A TRANSISTOR – to determine if it is good or bad. Can be done with an ohmmeter or transistor tester or by the substitution method.

***PRECAUTIONS* -** should be taken when working with transistors since they are subject to damage by electrical overloads, heat, humidity, and radiation.

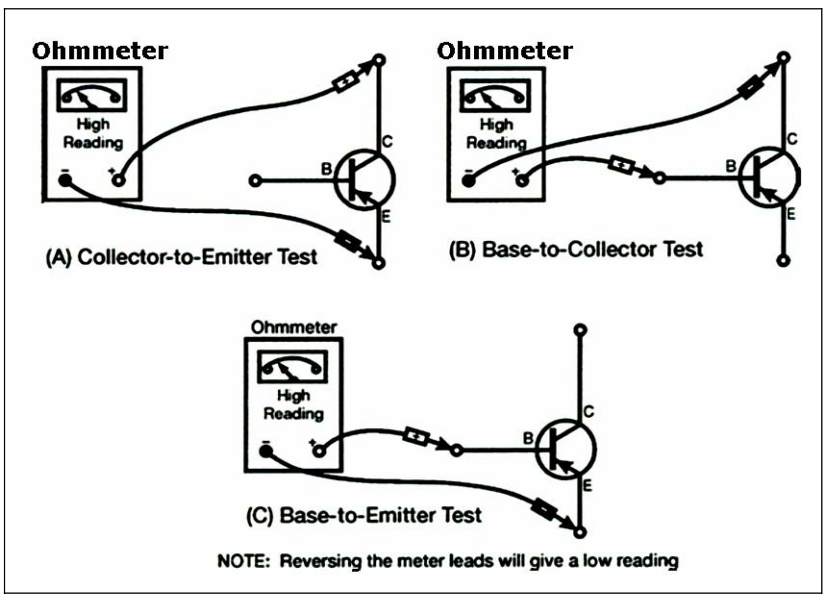
***TRANSISTOR LEAD IDENTIFICATION* -** plays an important part in transistor maintenance because before a transistor can be tested or replaced, its leads must be identified. Since there is NO standard method of identifying transistor leads, check some typical lead identification schemes or a transistor manual before attempting to replace a transistor.



TRANSISTOR GAIN TEST - can be made using an ohmmeter and a simple test circuit. The principle behind this test lies in the fact that little or no current will flow in a transistor between emitter and collector until the emitter-base junction is forward biased. A 10 to l resistance ratio in the test between meter readings indicates normal gain.



TRANSISTOR LEAKAGE TEST - can be made using an ohmmeter by measuring the base-emitter, base-collector, and collector-emitter forward and reverse resistances. Each section checked will have a low-forward resistance and a high-reverse resistance.

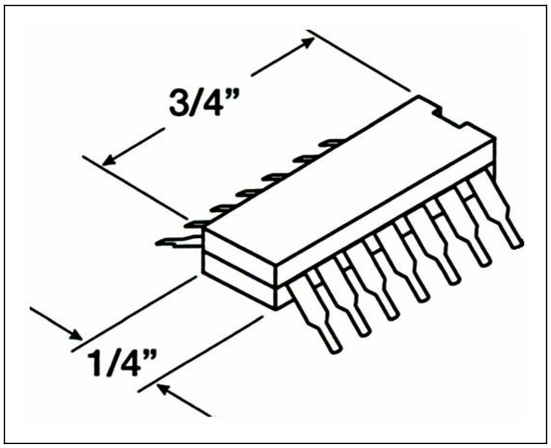


MICROELECTRONICS - a broad term used to describe the use of ICs to miniaturize electronic equipment.

PRINTED CIRCUIT BOARD - a flat, insulating surface upon which printed wiring and miniaturized components are connected in a predetermined design and attached to a CB.

MODULAR CIRCUITRY - an assembly technique in which PCBs are stacked and connected together to form a module. This technique increases the packaging density of circuit components and results in a considerable reduction in the size of electronic equipment.

INTEGRATED CIRCUIT - a device that integrates (combines) both active components (transistors, diodes, and so on) and passive components (resistors, capacitors, and so on) of a complete electronic circuit in a single chip.



INTEGRATED CIRCUIT BOARD - a plastic card on which ICs (chips) are mounted.

TWO BASIC TYPES OF ICs – two basic types are the hybrid and the monolithic.

IN THE MONOLITHIC IC - all elements (resistors, transistors, and so on) associated with the circuit are fabricated inseparably with a continuous piece of material (called the substrate).

IN THE HYBRID IC - the passive components (resistors and capacitors) are deposited onto a substrate (foundation) made of glass, ceramic, or other insulating material. Then the active components (diodes and transistors) are attached to the substrate and connected to the passive components using fine wire.

CHAPTER 2
CHECK-ON-LEARNING QUESTIONS

When you are satisfied that you have answered every question to the best of your ability, check your answers using Appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. What is the name given to the semiconductor device that has three or more elements?

2. Transistors are classified according to the arrangement of what?

3. In which direction does the arrow point on an NPN transistor?

4. What was the name of the very first transistor?

5. What is one of the most important parts of any transistor manufacturing process?

6. What is the simple way to remember on how to properly bias a transistor?

7. Ensure bias voltage polarities are correct before doing what?

8. What is the name for the majority carriers in N-type material?

9. Total current flow in the NPN transistor is through what?

10. What are the majority current carriers in a PNP transistor?

11. What happens when the emitter hole and a base electron meet in a PNP forward-biased junction?

12. What type of current flow is found in a PNP reverse-biased junction?

13. Name the two current loops in a transistor?

14. What is the name of the device that provides an increase in current, voltage, voltage, or power of a signal without appreciably altering the original signal?

15. Besides eliminating the emitter-base battery, what other advantages can different biasing methods offer?

16. What passes the AC input signal and blocks the DC voltage from the preceding circuit?

17. What is the primary difference between the NPN and PNP amplifiers?

18. Which biasing method is the most thermally unstable?

19. What type of bias is used where only moderate changes in ambient temperature are expected?

20. Why is degeneration sometimes desired in an amplifier?

21. What is the most widely used combination-bias system?

22. What amplifier class of operation allows collector current to flow during the complete cycle of the input?

23. The class AB operated amplifier is commonly used as what type of amplifier?

24. What two primary things determine the class of operation of an amplifier?

25. An amplifier has how many input sources?

26. What are the three transistor configurations?

27. Which transistor configuration provides a phase reversal between the input and output signals?

28. What is the name of current gain in the CE circuit?

29. Which transistor configuration has a current gain of less than 1?

30. What do you call the current gain in a common base circuit?

31. What transistor configuration is used mostly for impedance matching?

32. What is the range, in kilometers, of input resistance for common collector?

33. What is the range, in ohms, of output resistance for common collector?

34. What are three items of information normally included in the general description section of a specification sheet for a transistor?

35. What does the number "2" (before the letter "N") indicate in the JAN marking scheme?

36. What can you use to check if a transistor is good or bad.

37. What method for checking transistors is cumbersome when more than one transistor is bad in a circuit?

38. What is the most frequent cause of damage to a transistor when handled?

39. To what should you pay close attention when replacing a transistor?

40. What are the two most important parameters used for testing a transistor?

41. When you are testing the gain of an audio-frequency transistor with an ohmmeter, what is indicated by a 10-to-1 resistance ratio?

42. What are the two basic general classifications of ICs?

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Chapter 3
Special Devices

LEARNING OBJECTIVES

Learning objectives serve as a preview of the information you are expected to learn in this chapter. The comprehensive check-on-learning questions, found at the end of the chapter, are based on the objectives. Upon completion of this chapter, you will be able to perform the following learning objectives:

- Explain the basic operation and the major applications of the Zener diode.
- Describe the basic operation of the tunnel diode and the varactor.
- Explain the basic operation of the SCR and the triac and compare the advantages and disadvantages of each.
- List the five most commonly used optoelectronic devices and explain the uses of each.
- Describe the basic operation, applications, and major advantages of the unijunction transistor.
- Describe the basic operation, applications, and major advantages of the field-effect transistor and the metal-oxide semiconductor field-effect transistor.

INTRODUCTION TO SPECIAL DEVICES

3-1. If you consider the sensitive nature and the various interacting properties of semiconductors, it should not surprise you that solid state devices can be designed for many different purposes. In fact, there are many devices with special features and new designs are so frequently introduced that it would be beyond the scope of this chapter to describe all of the devices in use today. Therefore, this chapter will include a variety of representative devices that are used extensively in Army equipment to give you an idea of the diversity and versatility that has been made possible. These devices have been grouped into three categories (diodes, optoelectronic devices, and transistors). In this chapter we will cover and describe each device and its basic operation.

DIODES

3-2. Diodes are two-terminal semiconductors of various types that are used in seemingly endless applications. The operation of normal PN junction diodes has already been covered. However, there are a number of diodes with special properties with which you should be familiar. To cover all of the developments in the diode field would be impossible, so some of the more commonly used special diodes have been selected for explanation. These include Zener diodes, tunnel diodes, varactors, SCRs, and triacs.

Zener Diodes

3-3. When a PN junction diode is reverse biased, the majority carriers (holes in the P-material and electrons in the N-material) move away from the junction. The barrier or depletion region becomes wider (see Figure 3-1) and majority carrier current flow becomes very difficult across the high resistance of the wide depletion region. The presence of

minority carriers causes a small leakage current that remains nearly constant for all reverse voltages up to a certain value. Once this value has been exceeded, there is a sudden increase in the reverse current. The voltage at which the sudden increase in current occurs is called the BREAKDOWN VOLTAGE. At breakdown, the reverse current increases very rapidly with a slight increase in the reverse voltage. Any diode can be reverse biased to the point of breakdown, but not every diode can safely dissipate the power associated with breakdown. A Zener diode is a PN junction designed to operate in the reverse-bias breakdown region.

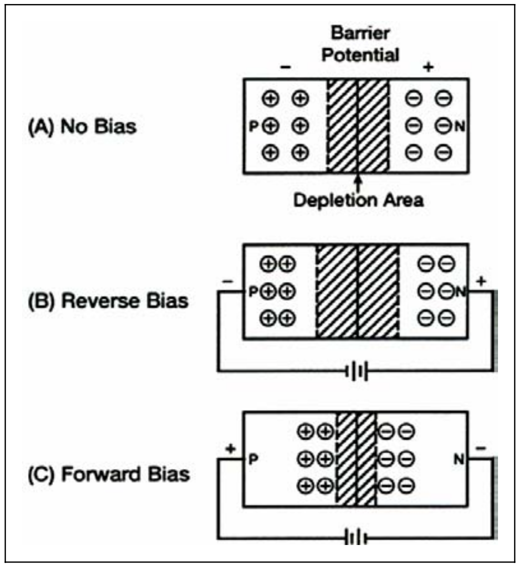


Figure 3-1. Effect of Bias on the Depletion Region of a PN Junction

3-4. There are two distinct theories used to explain the behavior of PN junctions during breakdown. These two theories are called ZENER EFFECT and the other is AVALANCHE EFFECT.

3-5. The ZENER EFFECT was first proposed by Dr. Carl Zener in 1934. According to Dr. Zener's theory, electrical breakdown in solid dielectrics occurs by a process called QUANTUM-MECHANICAL TUNNELING. The Zener effect accounts for the breakdown <u>below</u> 5 volts, while <u>above</u> 5 volts the breakdown is caused by the Avalanche effect. Although the Avalanche effect is now accepted as an explanation of diode breakdown, the term “Zener diode” is used to cover both types.

3-6. The true Zener effect in semiconductors can be described in terms of energy bands. However, only the two upper energy bands are of interest. The two upper bands (see Figure 3-2, view (A)) are called the CONDUCTION BAND and the VALENCE BAND.

3-7. The CONDUCTION BAND is a band in which the energy level of the electrons is high enough that the electrons will move easily under the influence of an external field. Since current flow is the movement of electrons, the readily mobile electrons in the conduction band are capable of maintaining a current flow when an external field in the form of a voltage is applied. Therefore, solid materials that have many electrons in the conduction band are called conductors.

3-8. The VALENCE BAND is a band in which the energy level is the same as the valence electrons of the atoms. Since the electrons in these levels are attached to the atoms, the electrons are not free to move around, as are the conduction band electrons. However,

with the proper amount of energy added, electrons in the valence band may be elevated to the conduction band energy level. To do this, the electrons must cross a gap that exists between the valence band energy level and the conduction band energy level. This gap is known as the FORBIDDEN ENERGY BAND or FORBIDDEN GAP. The energy difference across this gap determines whether a solid material will act as a conductor, a semiconductor, or an insulator.

3-9. A conductor is a material in which the forbidden gap is so narrow that it can be considered nonexistent. A semiconductor is a solid that contains a forbidden gap (see Figure 3-2, view (A)). Normally, a semiconductor has no electrons at the conduction band energy level. However, the energy provided by room temperature heat is enough energy to overcome the binding force of a few valence electrons and to elevate them to the conduction band energy level. The addition of impurities to the semiconductor material increases both the number of free electrons in the conduction band and the number of electrons in the valence band that can be elevated to the conduction band. Insulators are materials in which the forbidden gap is so large that practically no electrons can be given enough energy to cross the gap. Therefore, unless extremely large amounts of heat energy are available, these materials will not conduct electricity.

3-10. Figure 3-2, view (B) shows an energy diagram of a reverse-biased Zener diode. The energy bands of the P and N materials are naturally at different levels. However, reverse bias causes the valence band of the P material to overlap the energy level of the conduction band in the N material. Under this condition, the valence electrons of the P material can cross the extremely thin junction region at the overlap point without acquiring any additional energy. This action is called tunneling. When the breakdown point of the PN junction is reached, large numbers of minority carriers "tunnel" across the junction to form the current that occurs at breakdown. The tunneling phenomenon only takes place in heavily doped diodes such as Zener diodes.

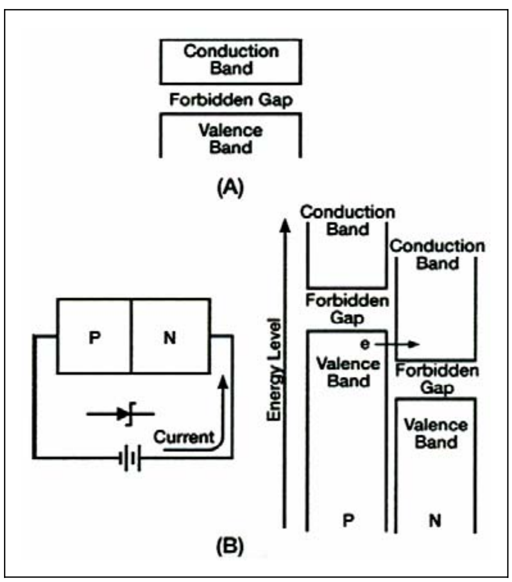


Figure 3-2. Energy Diagram for Zener Diode

3-11. The second theory of reverse breakdown effect in diodes is known as AVALANCHE EFFECT and occurs at reverse voltages <u>beyond</u> 5 volts. This type of breakdown diode has a depletion region that is deliberately made narrower than the

depletion region in the normal PN junction diode, but thicker than that in the Zener effect diode. The thicker depletion region is achieved by decreasing the doping level from the level used in Zener effect diodes. The breakdown is at a higher voltage because of the higher resistivity of the material. Controlling the doping level of the material during the manufacturing process can produce breakdown voltages ranging between 2 and 200 volts.

3-12. The mechanism of the Avalanche breakdown is different from that of the Zener effect. In the depletion region of a PN junction, thermal energy is responsible for the formation of electron-hole pairs. The leakage current is caused by the movement of minority electrons that is accelerated in the electric field across the barrier region. As the reverse voltage across the depletion region is increased, the reverse voltage eventually reaches a critical value. Once the critical or breakdown voltage has been reached, sufficient energy is gained by the thermally released minority electrons. This enables the electrons to rupture covalent bonds as they collide with lattice atoms. The released electrons are also accelerated by the electric field, resulting in the release of further electrons, and so on, in a chain or Avalanche effect. Figure 3-3 shows this process.

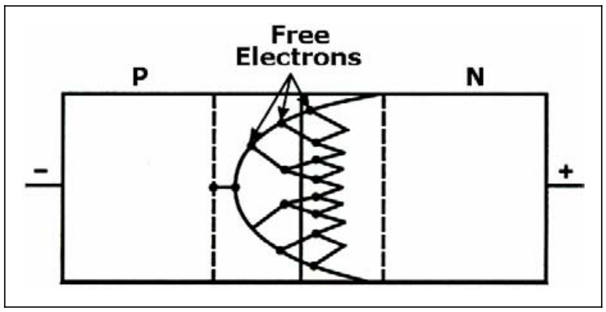


Figure 3-3. Avalanche Multiplication

3-13. For reverse voltage slightly higher than breakdown, the Avalanche effect releases an almost unlimited number of carriers so that the diode essentially becomes a short circuit. The current flow is limited in this region only by an external series current-limiting resistor. Operating a diode in the breakdown region does not damage it, as long as the maximum power dissipation rating of the diode is not exceeded. Removing the reverse voltage permits all carriers to return to their normal energy values and velocities.

3-14. See Figure 3-4, views (A) through (E) for some of the symbols used to represent Zener diodes. Notice that the polarity markings indicate electron flow is with the arrow symbol instead of against it as in a normal PN junction diode. This is because breakdown diodes are operated in the reverse-bias mode, which means that the current flow is by minority current carriers.

3-15. Zener diodes of various sorts are used for many purposes. Their most widespread use is as voltage regulators. Once the breakdown voltage of a Zener diode is reached, the voltage across the diode then remains almost constant regardless of the supply voltage. Therefore, they hold the voltage across the load at a constant level. This characteristic makes Zener diodes ideal voltage regulators and they are found in almost all solid state circuits in this capacity.

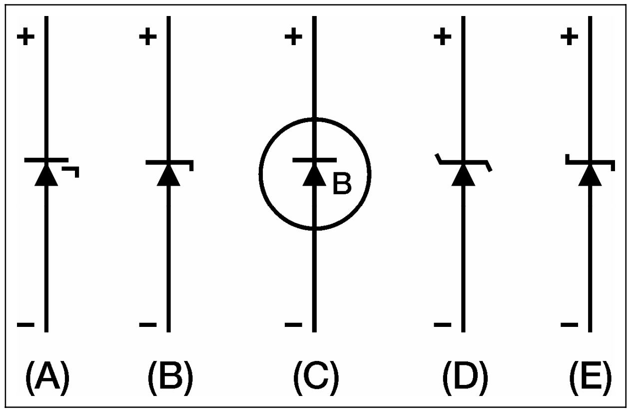


Figure 3-4. Schematic Symbols for Zener Diodes

The Tunnel Diode

3-16. In 1958, Leo Esaki, a Japanese scientist, discovered that if a semiconductor junction diode were heavily doped with impurities, it would have a region of negative resistance. The normal junction diode uses semiconductor materials that are lightly doped with one impurity atom for ten million semiconductor atoms. This low doping level results in a relatively wide depletion region. Conduction occurs in the normal junction diode only if the voltage applied to it is large enough to overcome the potential barrier of the junction.

3-17. In the TUNNEL DIODE, the semiconductor materials used in forming a junction are doped to the extent of one thousand impurity atoms for ten million semiconductor atoms. This heavy doping produces an extremely narrow depletion zone similar to that in the Zener diode. Because of the heavy doping, a tunnel diode exhibits an unusual current-voltage characteristic curve as compared with that of an ordinary junction diode. Figure 3-5 shows the characteristic curve for a tunnel diode.

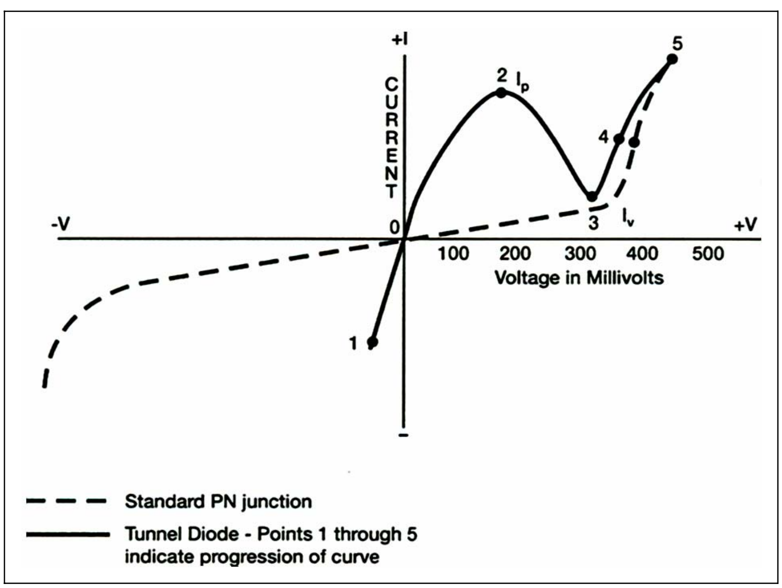


Figure 3-5. Characteristic Curve of a Tunnel Diode Compared to a Standard PN Junction

3-18. The three most important aspects of this characteristic curve are as follows:

- The forward current increase to a peak current (I_P) with a small, applied forward bias.
- The decreasing forward current with an increasing forward bias to a minimum valley current (I_V).
- The normal increasing forward current with further increases in the bias voltage.

The portion of the characteristic curve between I_P and I_V is the region of negative resistance. An explanation of why a tunnel diode has a region of negative resistance is best understood by using energy levels as in the previous explanation of the Zener effect.

3-19. Simply stated, the theory known as quantum-mechanical tunneling is an electron crossing a PN junction without having sufficient energy to do so otherwise. Because of the heavy doping, the width of the depletion region is only one-millionth of an inch. You might think of the process simply as an arc-over between the N- and the P-side across the depletion region.

3-20. Figure 3-6 shows the equilibrium energy level diagram of a tunnel diode with no bias applied. In view (A), the valence band of the P-material overlaps the conduction band of the N-material. The majority electrons and holes are at the same energy level in the equilibrium state. If there is any movement of current carriers across the depletion region due to thermal energy, the net current flow will be zero because equal numbers of current carriers flow in opposite directions. In view (B), the zero net current flow is marked by a "0" on the current-voltage curve.

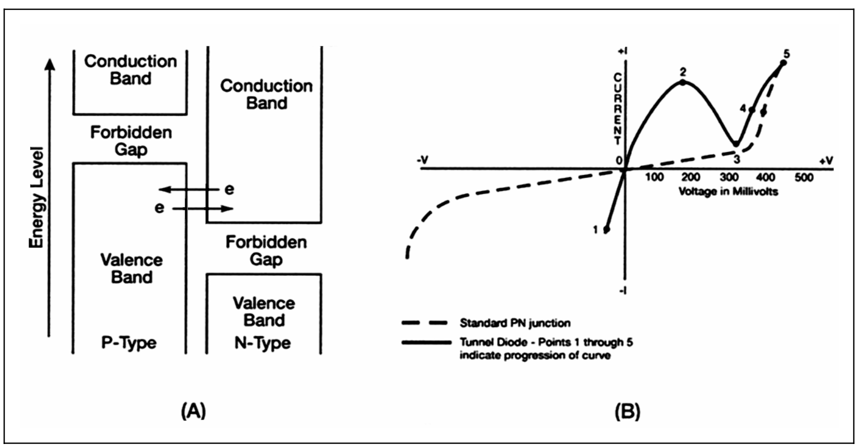


Figure 3-6. Tunnel Diode Energy Diagram With No Bias

3-21. Figure 3-7, view (A), shows the energy diagram of a tunnel diode with a small forward bias (50 millivolts) applied. The bias causes unequal energy levels between some of the majority carriers at the energy band overlap point, but not enough of a potential difference to cause the carriers to cross the forbidden gap in the normal manner. Since the valence band of the P-material and the conduction band of the N-material still overlap, current carriers tunnel across at the overlap and cause a substantial current flow. The amount of current flow is marked by point 2 on the curve in view (B). In view (A) the amount of overlap between the valence band and the conduction band decreased when forward bias was applied.

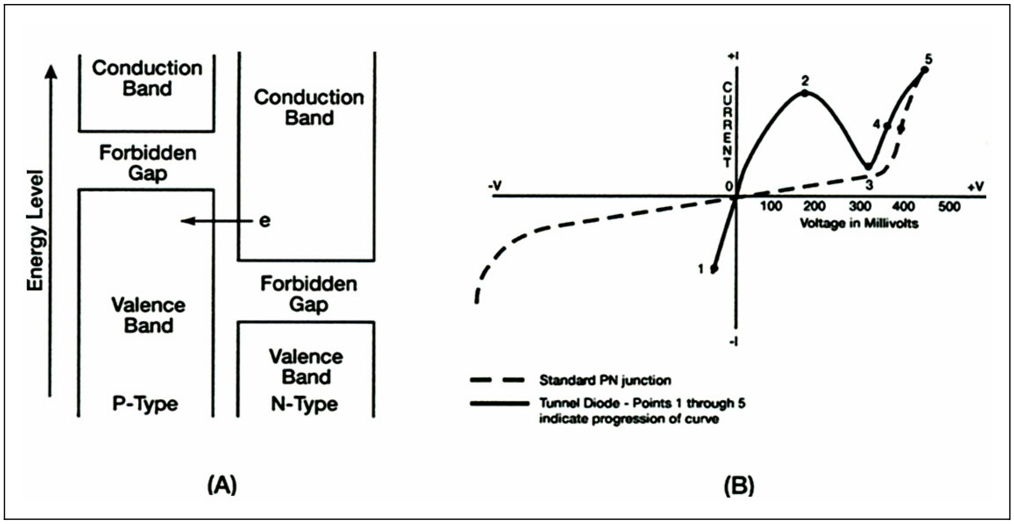


Figure 3-7. Tunnel Diode Energy Diagram With 50 Millivolts Bias

3-22. Figure 3-8, view (A), is the energy diagram of a tunnel diode in which the forward bias has been increased to 450 millivolts. As you can see, the valence band and the conduction band no longer overlap at this point and tunneling can no longer occur. The portion of the curve in view (B) from point 2 to point 3 shows the decreasing current that occurs as the bias is increased and the area of overlap becomes smaller. As the overlap between the two energy bands becomes smaller, fewer and fewer electrons can tunnel across the junction. The portion of the curve between point 2 and point 3 in which current decreases as the voltage increases is the negative resistance region of the tunnel diode.

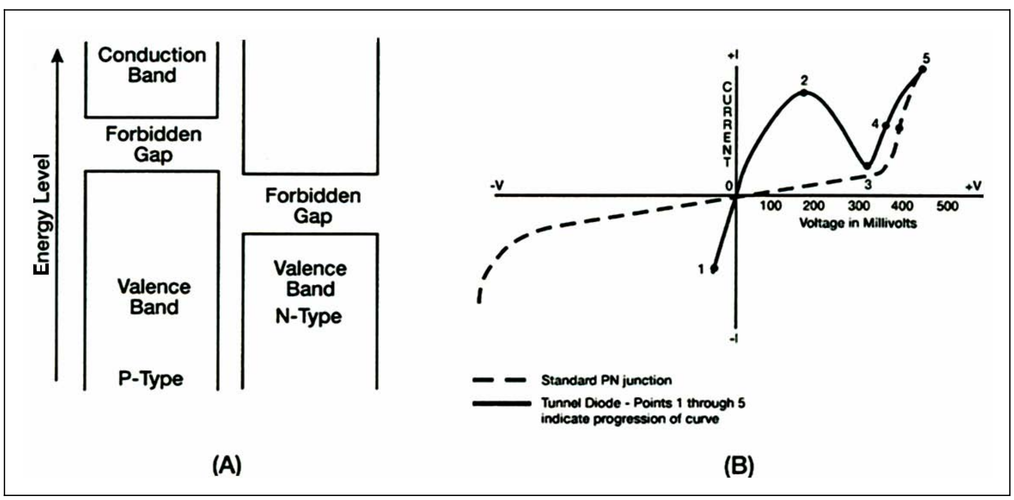


Figure 3-8. Tunnel Diode Energy Diagram With 450 Millivolts Bias

3-23. Figure 3-9, view (A), is the energy diagram of a tunnel diode in which the forward bias has been increased even further. The energy bands no longer overlap and the diode operates in the same manner as a normal PN junction, as shown by the portion of the curve in view (B) from point 3 to point 4.

3-24. The negative resistance region is the most important and most widely used characteristic of the tunnel diode. A tunnel diode biased to operate in the negative resistance region can be used as either an oscillator or an amplifier in a wide range of frequencies and applications. Very high frequency applications using the tunnel diode are possible because the tunneling action occurs so rapidly that there is no transit time effect and therefore no signal distortion. Tunnel diodes are also used extensively in high-speed switching circuits because of the speed of the tunneling action.

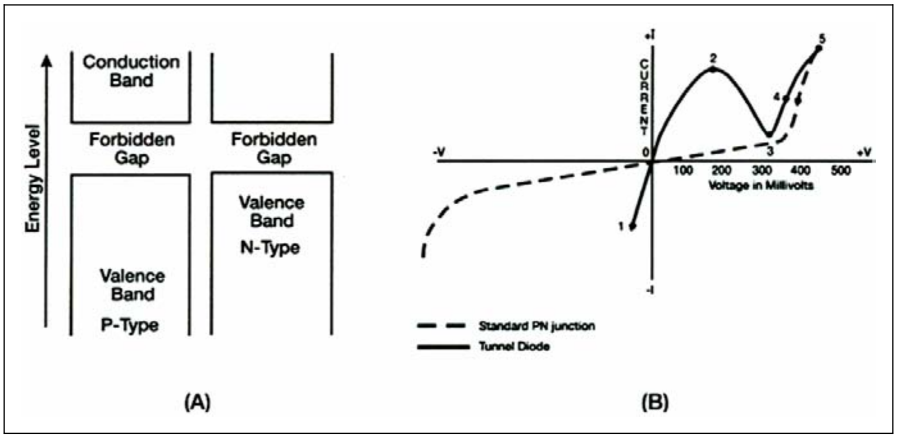


Figure 3-9. Tunnel Diode Energy Diagram With 600 Millivolts Bias

3-25. Several schematic symbols are used to indicate tunnel diodes. These symbols are shown in Figure 3-10, views (A) through (D).

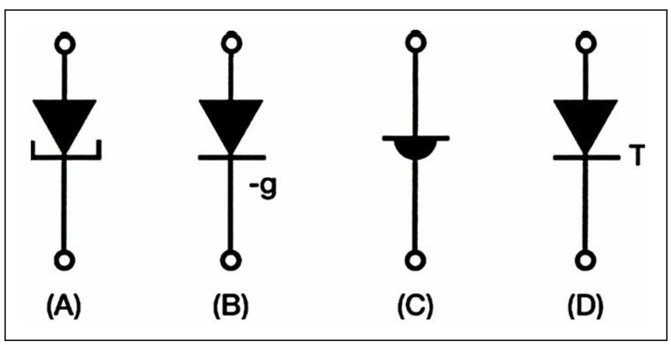


Figure 3-10. Tunnel Diode Schematic Symbols

Varactor

3-26. The VARACTOR, or varicap, as the schematic drawing in Figure 3-11 suggests, is a diode that behaves like a variable capacitor, with the PN junction functioning like the dielectric and plates of a common capacitor. Understanding how the varactor operates is an important prerequisite to understanding field-effect transistors, which will be covered later in this chapter.

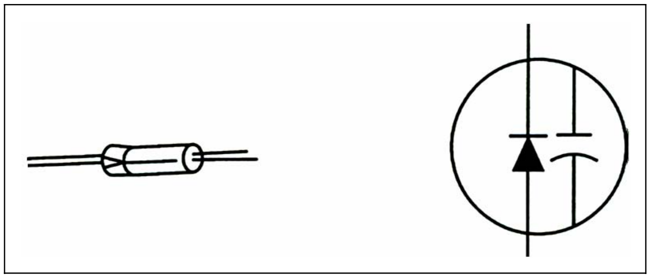


Figure 3-11. Varactor Diode

3-27. Figure 3-12 shows a PN junction. Surrounding the junction of the P and N materials is a narrow region void of positive and negative charged current carriers. This area is called the depletion region.

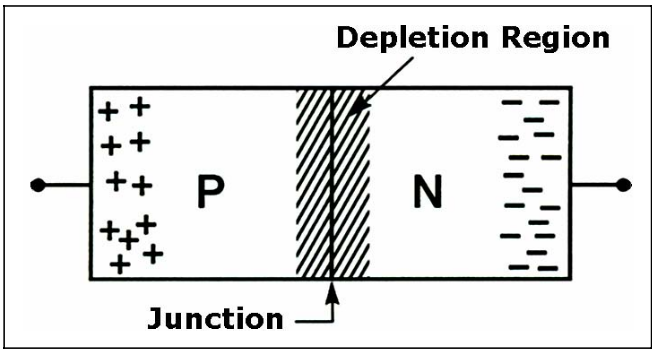


Figure 3-12. PN Junction

3-28. The size of the depletion region in a varactor diode is directly related to the bias. Forward biasing makes the region smaller by repelling the current carriers toward the PN junction. If the applied voltage is large enough (about .5 volts for silicon material), the negative particles will cross the junction and join with the positive particles (see Figure 3-13). This forward biasing causes the depletion region to decrease, producing a low resistance at the PN junction and a large current flow across it. This is the condition for a forward-biased diode. On the other hand, if reverse-bias voltage is applied to the PN junction, the size of its depletion region increases as the charged particles on both sides move away from the junction. This condition (see Figure 3-14) produces a high resistance between the terminals and allows little current flow (only in the microampere range). This is the operating condition for the varactor diode, which is nothing more than a special PN junction.

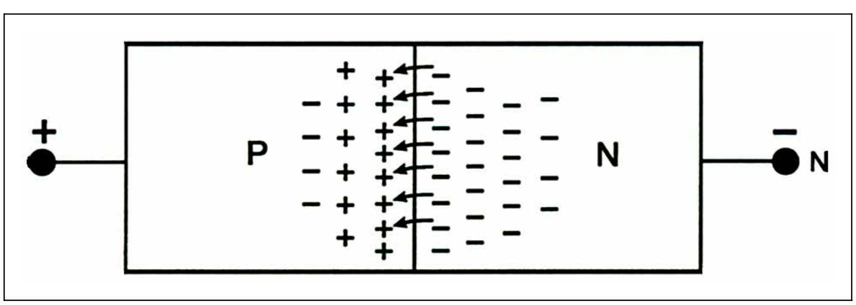


Figure 3-13. Forward-biased PN Junction

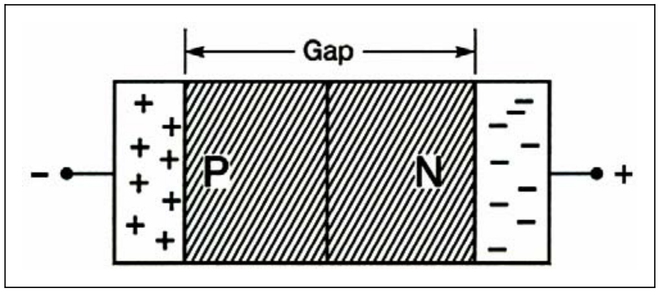


Figure 3-14. Reverse-biased PN Junction

3-29. As Figure 3-14 shows, the insulation gap formed by reverse biasing the varactor is comparable to the layer of dielectric material between the plates of a common capacitor. The formula (shown below) used to calculate capacitance could also be applied to both the varactor and the capacitor. In this case, the size of the insulation gap of the varactor, or depletion region, is substituted for the distance between the plates of the capacitor. By varying the reverse-bias voltage applied to the varactor, the width of the "gap" may be varied. An increase in reverse bias increases the width of the gap (d) that reduces the capacitance (C) of the PN junction. Therefore, the capacitance of the varactor is inversely proportional to the applied reverse bias.

$$C = \frac{AK}{d}$$

Where:

A = plate area

K = a constant value

d = distance between plates

3-30. The ratio of varactor capacitance to reverse-bias voltage change may be as high as 10 to 1. Figure 3-15 shows one example of the voltage-to-capacitance ratio. View (A) shows that a reverse bias of 3 volts produces a capacitance of 20 picofarads in the varactor. If the reverse bias is increased to 6 volts, as shown in view (B), the depletion region widens and capacitance drops to 5 picofarads. Each 1-volt increase in bias voltage causes a 5-picofarad decrease in the capacitance of the varactor. The ratio of change is therefore 5 to 1. Of course any <u>decrease</u> in applied bias voltage would cause a proportionate <u>increase</u> in capacitance, as the depletion region narrows. Notice that the value of the capacitance is small in the picofarad range.

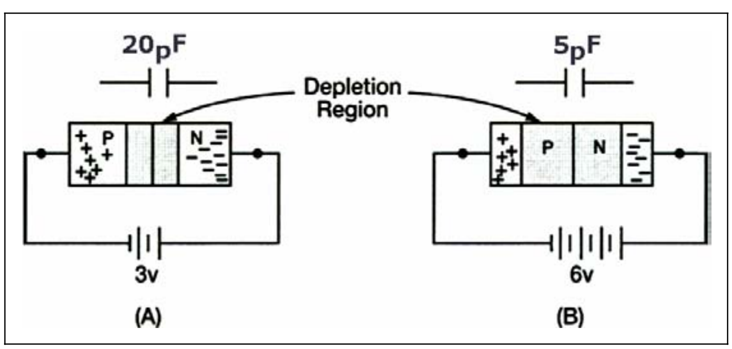


Figure 3-15. Varactor Capacitance Versus Bias Voltage

3-31. In general, varactors are used to replace the old style variable capacitor tuning. They are used in tuning circuits of more sophisticated communication equipment and in other circuits where variable capacitance is required. One advantage of the varactor is that it allows a DC voltage to be used to tune a circuit for simple remote control or automatic tuning functions. One such application of the varactor is as a variable tuning capacitor in a receiver or transmitter tank circuit (see Figure 3-16).

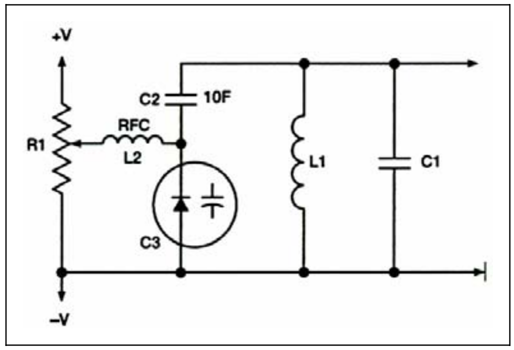


Figure 3-16. Varactor Tuned Resonant Circuit

3-32. Figure 3-16 also shows a DC voltage felt at the wiper of potentiometer R1 that can be adjusted between +V and -V. The DC voltage, passed through the low resistance of radio frequency choke L2, acts to reverse bias varactor diode C3. The capacitance of C3 is in series with C2, and the equivalent capacitance of C2 and C3 is in parallel with tank circuit L1-C1. Therefore, any variation in the DC voltage at R1 will vary both the capacitance of C3 and the resonant frequency of the tank circuit. The RF choke provides high inductive reactance at the tank frequency to prevent tank loading by R1. C2 acts to block DC from the tank as well as to fix the tuning range of C3.

3-33. An ohmmeter can be used to check a varactor diode in a circuit. A high reverse-bias resistance and a low forward-bias resistance with a 10 to 1 ratio in reverse-bias to forward-bias resistance is considered normal.

Silicon Controlled Rectifier

3-34. The SILICON CONTROLLED RECTIFIER is one of the families of semiconductors that include transistors and diodes. Figure 3-17, views (A) and (B) shows a drawing of an SCR and its schematic representation. Not all SCRs use the casing shown. However, this is typical of most of the high-power units.

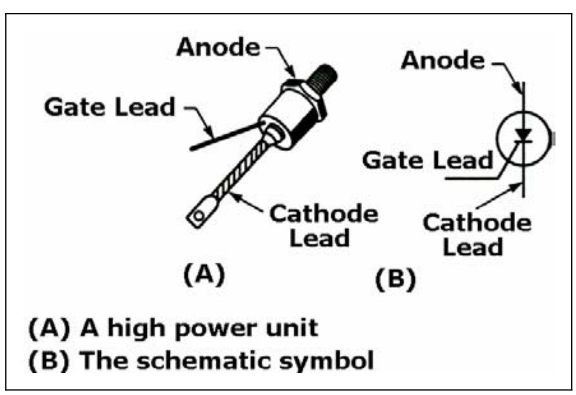


Figure 3-17. Silicon Controlled Rectifier Schematic

3-35. Although it is not the same as either a diode or a transistor, the SCR combines features of both. Circuits using transistors or rectifier diodes may be greatly improved in some instances through the use of SCRs.

3-36. The basic purpose of the SCR is to function as a switch that can turn on or off small or large amounts of power. It performs this function with no moving parts that wear out and no points that require replacing. There can be a tremendous power gain in the SCR; in some units a very small triggering current is able to switch several hundred amperes without exceeding its rated abilities. The SCR can often replace much slower and larger mechanical switches. It even has many advantages over its more complex and larger electronic-tube equivalent, the thyratron.

3-37. The SCR is an extremely fast switch. It is difficult to cycle a mechanical switch several hundred times a minute. However, some SCRs can be switched 25,000 times a second. It takes just "microseconds (millionths of a second) to turn on or off these units. Varying the time that a switch is on as compared to the time that it is off regulates the amount of power flowing through the switch. Since most devices can operate on pulses of power (AC is a special form of alternating positive and negative pulses), the SCR can be used readily in control applications. Motor-speed controllers, inverters, remote switching units, controlled rectifiers, circuit overload protectors, latching relays, and computer logic circuits all use the SCR.

3-38. The SCR is made up of four layers of semiconductor material arranged PNPN (see Figure 3-18, view (A). In function, the SCR has much in common with a diode. However, the theory of operation of the SCR is best explained in terms of transistors.

3-39. Consider the SCR as a transistor pair, one PNP and the other NPN (see Figure 3-18, view B). The anode "A", is attached to the upper P-layer; the cathode "C", is part of the lower N-layer; and the gate terminal "G", goes to the P-layer of the NPN triode.

3-40. In operation (see Figure 3-18, view C)) the collector of Q2 drives the base of Q1, while the collector of Q1 feeds back to the base of Q2. β_1 (Beta) is the current gain of Q1 and β_2 is the current gain of Q2. The gain of this positive feedback loop is their product (β_1 x β_2). When the product is less than one, the circuit is stable; if the product is greater than unity, the circuit is regenerative. A small negative current applied to terminal G will bias the NPN transistor into cutoff, and the loop gain is less than unity. Under these conditions, the only current that can exist between output terminals A and C is the very small cutoff collector current of the two transistors. For this reason the impedance between A and C is very high.

3-41. When a positive current is applied to terminal G, transistor Q2 is biased into conduction, causing its collector current to rise. Since the current gain of Q2 increases with increased collector current, a point (called the breakdown point) is reached where the loop gain equals unity and the circuit becomes regenerative. At this point, collector current of the two transistors rapidly increases to a value limited only by the external circuit. Both transistors are driven into saturation, and the impedance between A and C is very low. The positive current applied to terminal G, which served to trigger the self-regenerative action, is no longer required since the collector of PNP transistor Q1 now supplies more than enough current to drive Q2. The circuit will remain on until it is turned off by a reduction in the collector current to a value below that necessary to maintain conduction.

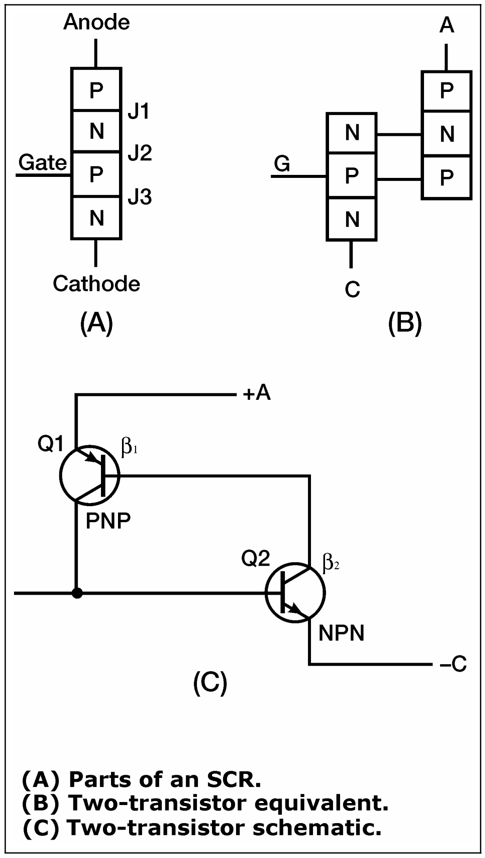


Figure 3-18. SCR Structure

3-42. Figure 3-19 shows the characteristic curve for the SCR. With no gate current, the leakage current remains very small as the forward voltage from cathode to anode is increased until the breakdown point is reached. Here the center junction breaks down, the SCR begins to conduct heavily, and the drop across the SCR becomes very low.

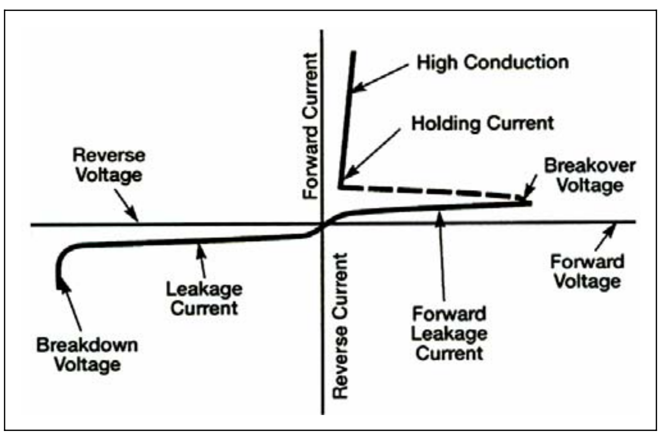


Figure 3-19. Characteristic Curve for an SCR

3-43. Figure 3-20 shows the effect of a gate signal on the firing of an SCR. Breakdown of the center junction can be achieved at speeds approaching a microsecond by applying an appropriate signal to the gate lead, while holding the anode voltage constant. After

breakdown, the voltage across the device is so low that the current through it from cathode to anode is essentially determined by the load it is feeding.

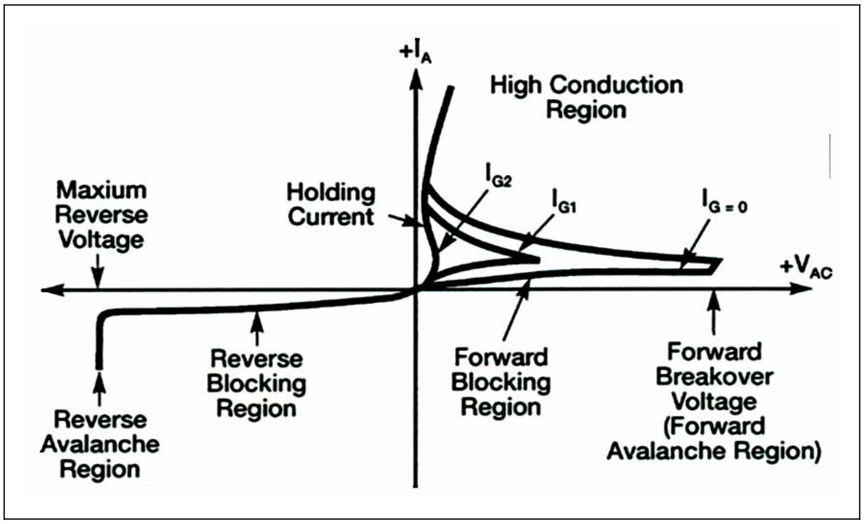


Figure 3-20. SCR Characteristic Curve With Various Gate Signals

3-44. The important thing to remember is that a small current from gate to cathode can fire or trigger the SCR, changing it from practically an open circuit to a short circuit. The only way to change it back again (to commutate it) is to reduce the load current to a value less than the minimum forward-bias current. Gate current is required only until the anode current has completely built up to a point sufficient to sustain conduction (about five microseconds in resistive-load circuits). After conduction from cathode to anode begins, removing the gate current has no effect.

3-45. The basic operation of the SCR can be compared to that of the thyratron. The thyratron is an electron tube, normally gas filled, that uses a filament or a heater. The SCR and the thyratron function in almost the same manner. Figure 3-21 shows the schematic of each with the corresponding elements labeled. In both types of devices, control by the input signal is lost after they are triggered. The control grid (thyratron) and the gate (SCR) have no further affect on the magnitude of the load current after conduction begins. The load current can be interrupted by one or more of the following three methods:

- The load circuit must be opened by a switch.
- The plate (anode) voltage must be reduced below the ionizing potential of the gas (thyratron).
- The forward-bias current must be reduced below a minimum value required to sustain conduction (SCR).

The input resistance of the SCR is relatively low (approximately 100 ohms) and requires a current for triggering. The input resistance of the thyratron is exceptionally high and requires a voltage input to the grid for triggering action.

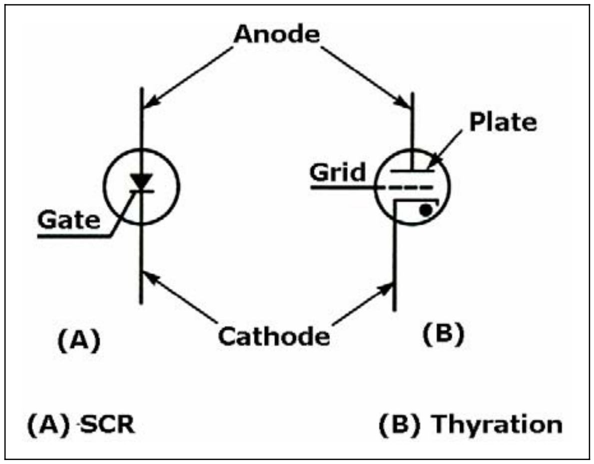


Figure 3-21. Comparison of an SCR and a Thyratron

3-46. There are many applications of the SCR as a rectifier. In fact, its many applications as a rectifier give this semiconductor device its name. When AC is applied to a rectifier, only the positive or negative halves of the sine waves flow through. All of each positive or negative half cycle appears in the output. However, when an SCR is used, the controlled rectifier may be turned on at any time during the half cycle, thereby controlling the amount of DC power available from zero to maximum (see Figure 3-22). Since the output is actually DC pulses, suitable filtering can be added if continuous DC is needed. Therefore, any DC operated device can have controlled amounts of power applied to it. Notice that the SCR must be turned on at the desired time for each cycle.

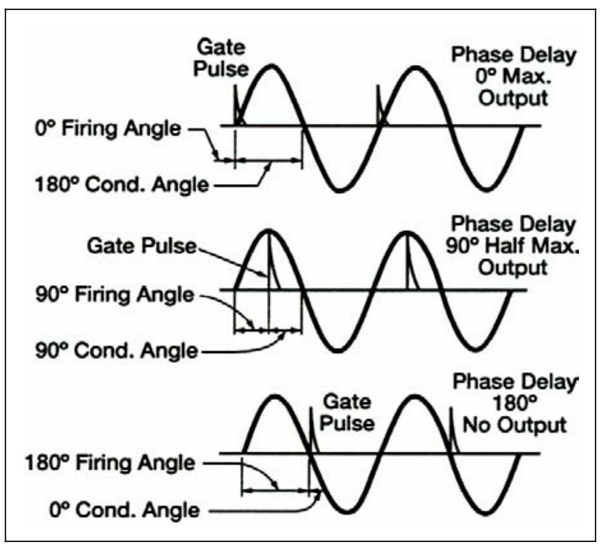


Figure 3-22. SCR Gate Control Signals

3-47. When an AC power source is used, the SCR is turned off automatically, since current and voltage drop to zero every half cycle. By using one SCR on positive alternations and one on negative, full-wave rectification can be accomplished, and control is obtained over the entire sine wave. The SCR serves in this application just as its name implies (as a controlled rectifier of AC voltage).

Triac

3-48. The TRIAC is a three-terminal device similar in construction and operation to the SCR. The triac controls and conducts current flow during both, instead of only one, alternations of an AC cycle. See Figure 3-23 for a comparison of the schematic symbols for the SCR and the triac. Both the SCR and the triac have a gate lead. However, in the triac the lead on the same side as the gate is “main terminal 1,” and the lead opposite the gate is “main terminal 2.” This method of lead labeling is necessary because the triac is essentially two SCRs back-to-back, with a common gate and common terminals. Each terminal is, in effect, the anode of one SCR and the cathode of another, and either terminal can receive an input. In fact, by connecting two actual SCRs (see Figure 3-24), the functions of a triac can be duplicated. The result is a three-terminal device identical to the triac. The common anode-cathode connections form main terminals 1 and 2 and the common gate forms terminal 3.

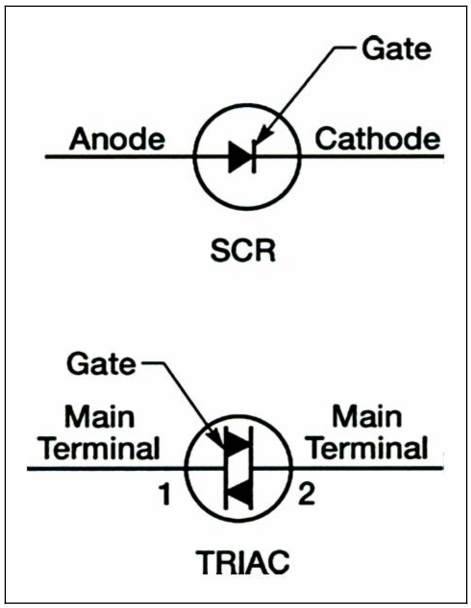


Figure 3-23. Comparison of SCR and Triac Symbols

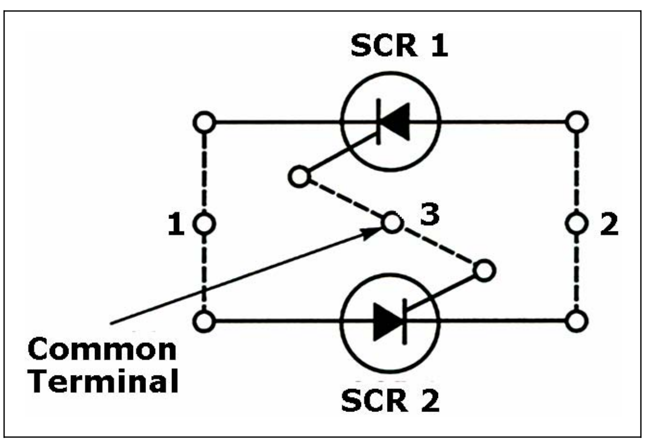


Figure 3-24. Back-to-back SCR Equivalent Circuit

3-49. Figure 3-25 shows the basic circuit, which shows the difference in current control between the SCR and the triac by comparing their operation. In the circuit shown in Figure 3-25, view (A), the SCR is connected in the familiar half-wave arrangement. Current will flow through the load resistor (R_L) for one alternation of each input cycle. Diode CR1 is necessary to ensure a positive trigger voltage. In the circuit shown in Figure 3-25, view (B), with the triac inserted in the place of the SCR, current flows through the load resistor during both alternations of the input cycle. Since either alternation will trigger the gate of the triac, CR1 is not required in the circuit.

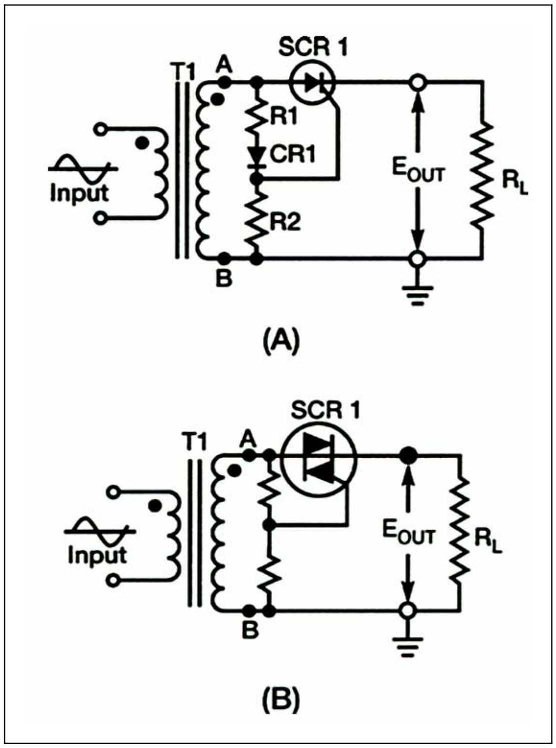


Figure 3-25. Comparison of SCR and Triac Circuits

3-50. Current flowing through the load will reverse direction for half of each input cycle. To clarify this difference, Figure 3-26 shows a comparison of the waveforms seen at the input, gate, and output points of the two devices.

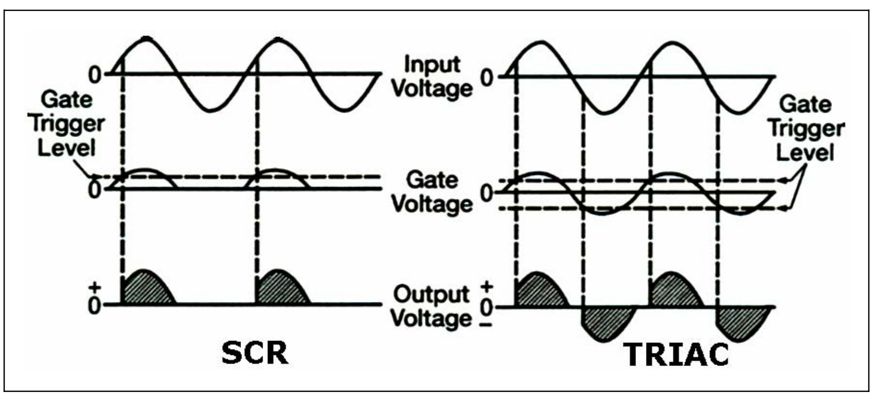


Figure 3-26. Comparison of SCR and Triac Waveforms

Optoelectronic Devices

3-51. OPTOELECTRONIC devices either produce light or use light in their operation. The first of these, the LIGHT EMITTING DIODE, was developed to replace the fragile, short-life incandescent light bulbs used to indicate on/off conditions on panels. A LED is a diode which, when forward biased, produces visible light. The light may be red, green, or amber, depending upon the material used to make the diode.

3-52. Figure 3-27 shows an LED and its schematic symbol. The LED is designated by a standard diode symbol with two arrows pointing away from the cathode. The arrows indicate light leaving the diode. The circuit symbols for all optoelectronic devices have arrows pointing either towards them, if they use light, or away from them, if they produce light. The LED operating voltage is small (about 1.6 volts forward bias and generally about 10 milliamperes). The life expectancy of the LED is very long, over 100,000 hours of operation.

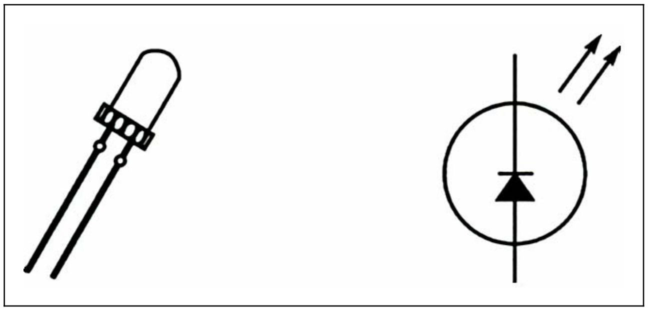


Figure 3-27. Light Emitting Diode

3-53. LEDs are widely used as “power on” indicators of current and as displays for pocket calculators, digital voltmeters, and frequency counters. For use in calculators and similar devices, LEDs are typically placed together in seven-segment displays. Figure 3-28, view (A) shows the display with the seven LED segments labeled A through G. Figure 3-28, view (B) shows a schematic for a common-anode display. All anodes in a display are internally connected. The segments can be lit in different combinations to form any number from “0” through “9.” When a negative voltage is applied to the proper segments, a number is formed. For example, if negative voltage is applied to all segments except that of LED “E,” the number “9” is produced (see Figure 3-29, view (A)). If the negative voltage is changed and applied to all segments except LED “B,” the number “9” changes to “6” (see Figure 3-29, view (B)).

3-54. Seven-segment displays are also available in common-cathode form, in which all cathodes are at the same potential. When replacing LED displays, you must ensure the replacement display is of the same type as the faulty display. Since both types look alike, you should always check the manufacturer's number.

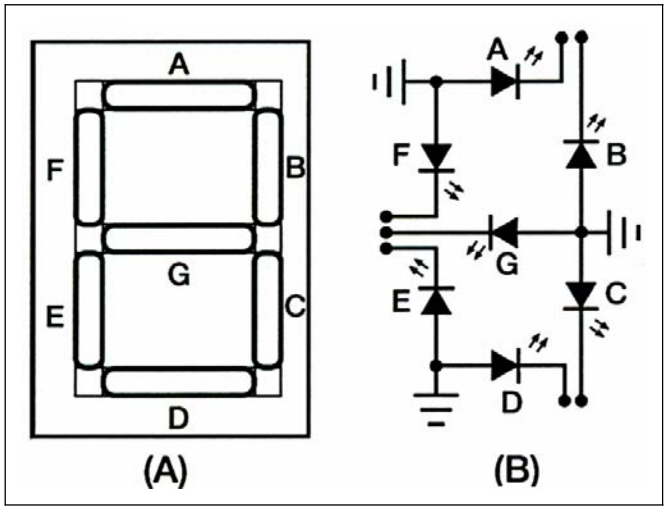


Figure 3-28. Seven-segment LED Display

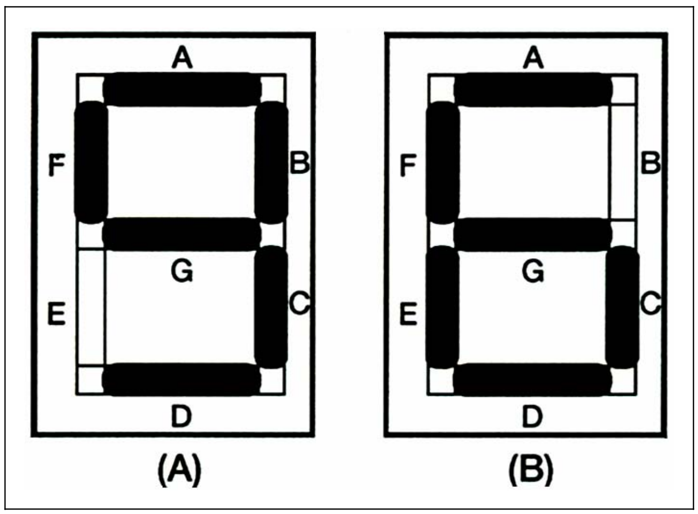


Figure 3-29. Seven-segment LED Display Examples

3-55. LED seven-segment displays range from the very small, often not much larger than standard typewritten numbers, to about an inch. Several displays may be combined in a package to show a series of numbers (see Figure 3-30).

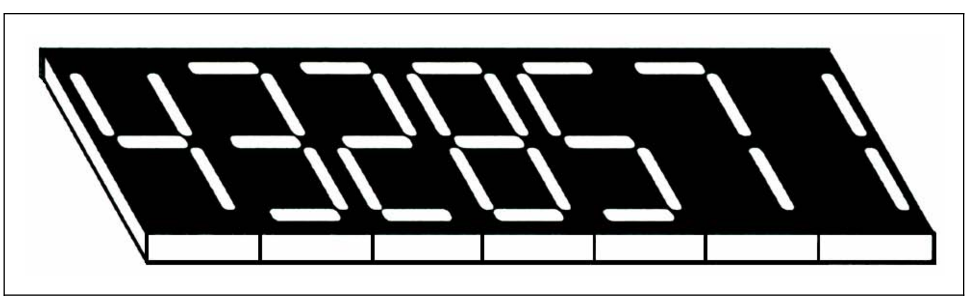


Figure 3-30. Stacked Seven-segment Display

3-56. Another special optoelectronic device in common use today is the PHOTODIODE. Unlike the LED, which produces light, the photodiode uses light to accomplish special circuit functions. Basically, the photodiode is a light-controlled variable resistor. In total darkness, it has a relatively high resistance and therefore conducts little current. However, when the PN junction is exposed to an external light source, internal resistance decreases and current flow increases. The photodiode is operated with reverse bias and conducts current in direct proportion to the intensity of the light source.

3-57. Figure 3-31 shows a photodiode with its schematic symbol. The arrows pointing toward the symbol indicate that light is required for operation of the device. A light source is aimed at the photodiode through a transparent “window” placed over the semiconductor chip. Switching the light source on or off changes the conduction level of the photodiode. Varying the light intensity, controls the amount of conduction. Since photodiodes respond quickly to changes in light intensity, they are extremely useful in digital applications such as computer card readers, paper tape readers, and photographic light meters. They are also used in some types of optical scanning equipment.

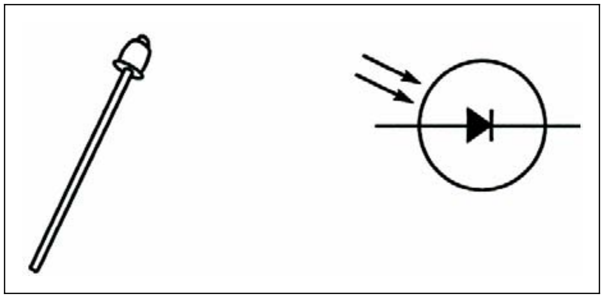


Figure 3-31. Photodiode

3-58. A second optoelectronic device that conducts current when exposed to light is the PHOTOTRANSISTOR. A phototransistor is much more sensitive to light and produces more output current for a given light intensity that does a photodiode. Figure 3-32 shows one type of phototransistor that is made by placing a photodiode in the base circuit of an NPN transistor. Light falling on the photodiode changes the base current of the transistor, causing the collector current to be amplified. Phototransistors may also be of the PNP type, with the photodiode placed in the base-collector circuit.

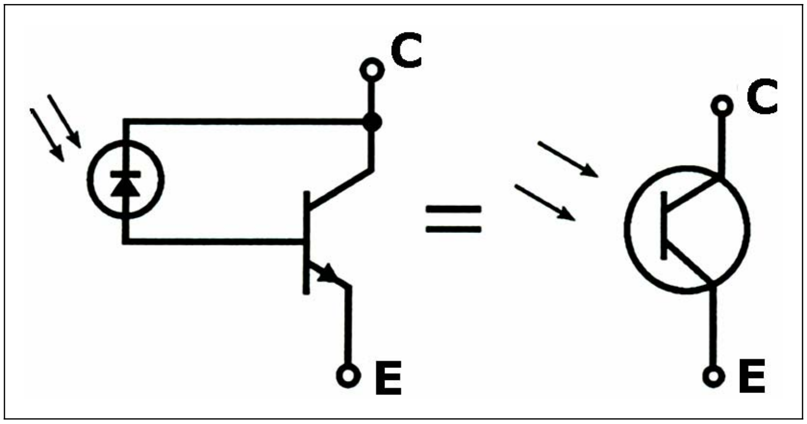


Figure 3-32. Phototransistor

3-59. Figure 3-33 shows the schematic symbols for the different types of phototransistors. Phototransistors may be of the two-terminal type, in which the light intensity on the photodiode alone determines the amount of conduction. They may also be of the three-terminal type, which have an added base lead that allows an electrical bias to be applied to the base. The bias allows an optimum transistor conduction level, and therefore compensates for ambient (normal room) light intensity.

3-60. An older device that uses light similar to the photodiode is the photoconductive cell, or PHOTOCELL. Figure 3-34 shows the cell along with its schematic symbol. Like the photodiode, the photocell is a light-controlled variable resistor. However, a typical light to dark resistance ratio for a photocell is 1:1,000. This means that its resistance could range from 1,000 ohms in the light to 1,000 kilohms in the dark, or from 2,000 ohms in the light to 2,000 kilohms in the dark, and so forth. Of course, other ratios are also available. Photocells are used in many types of control and timing circuits (for example, the automatic street light controllers in most cities).

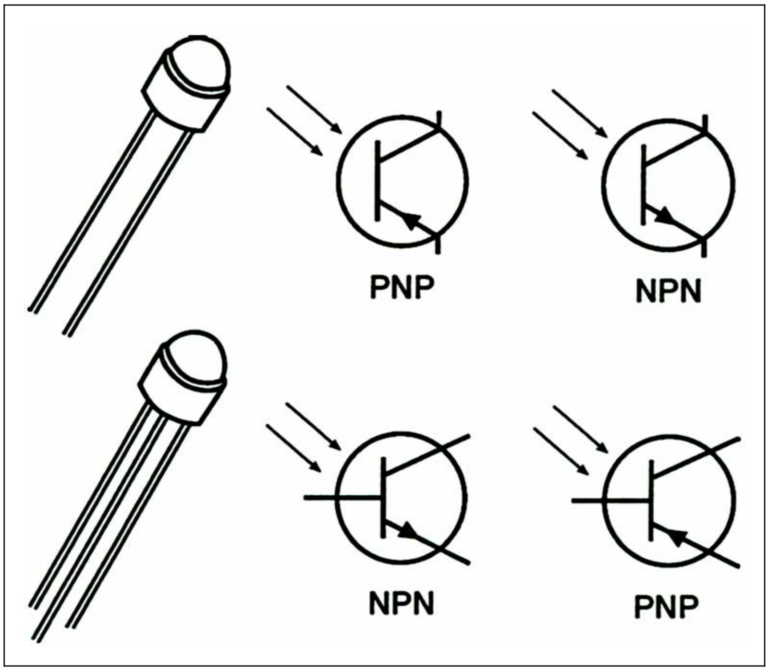


Figure 3-33. Two-terminal and three-terminal Phototransistors

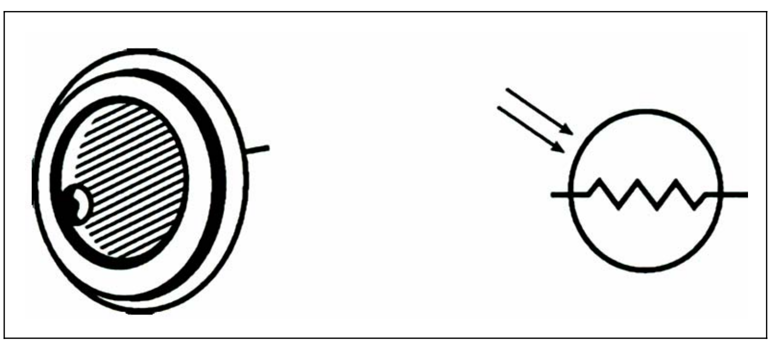


Figure 3-34. Photocell

3-61. The photovoltaic cell, or SOLAR CELL, is a device that converts light energy into electrical energy. Figure 3-35 shows an example of a solar cell and its schematic symbol. The symbol is similar to that of a battery. The device itself acts much like a battery when exposed to light and produces about .45 volts across its terminals, with current capacity determined by its size. As with batteries, solar cells may be connected in series or parallel to produce higher voltages and currents. The device is finding widespread application in communications satellites and solar-powered homes.

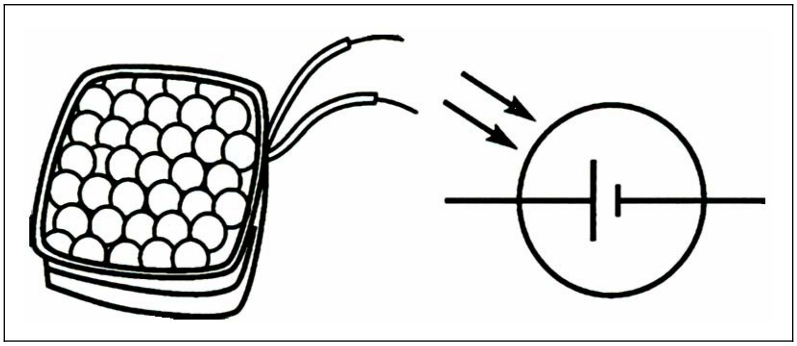


Figure 3-35. Solar Cell

3-62. When it is necessary to block the voltage between one electronic circuit and another, and transfer the signal at the same time, an amplifier coupling capacitor is often used (see Figure 3-36). Although this method of coupling does block DC between the circuits, voltage isolation is not complete. A newer method, making use of optoelectronic devices to achieve electrical isolation, is the OPTICAL COUPLER (see Figure 3-37). The coupler is composed of an LED and a photodiode contained in a light-conducting medium. As the polarity signs in Figure 3-37 show, the LED is forward biased, while the photodiode is reverse biased. When the input signal causes current through the LED to increase, the light produced by the LED increases. This increased light intensity causes current flow through the photodiode to increase. In this way, changes in input current produce proportional changes in the output, even though the two circuits are electrically isolated.

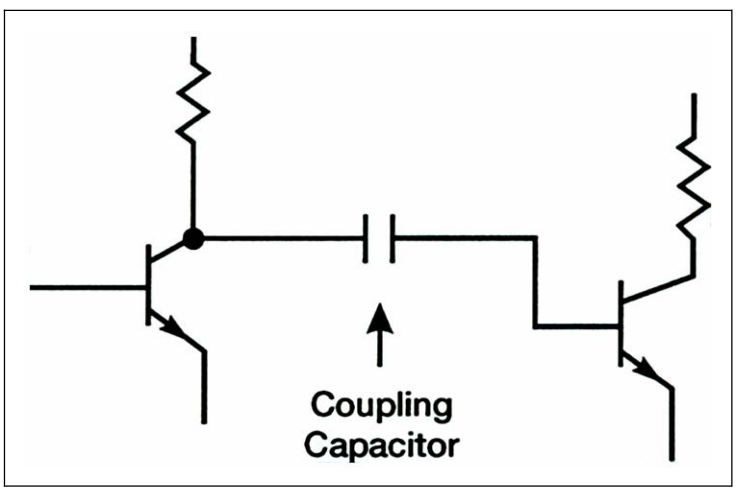


Figure 3-36. DC Blocking With a Coupling Capacitor

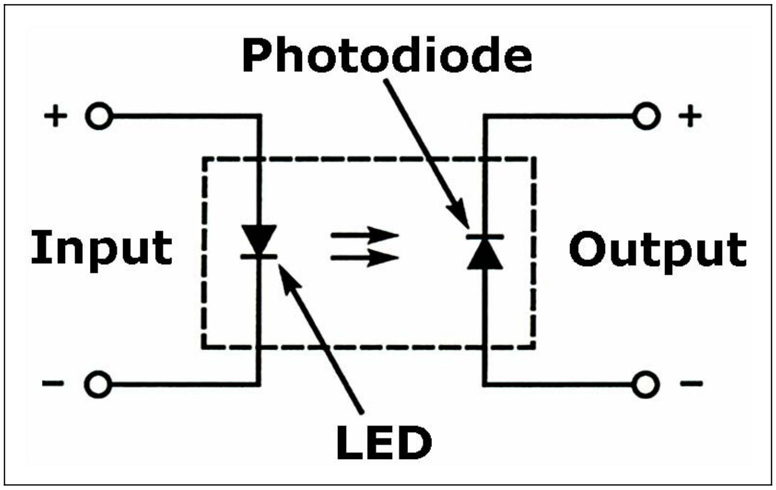


Figure 3-37. Optical Coupler

3-63. The optical coupler is suitable for frequencies in the low megahertz range. The photodiode type shown above can handle only small currents. However, other types of couplers, combining phototransistors with the SCR, can be used where more output is required. Optical couplers are replacing transformers in low-voltage and low-current applications. Sensitive digital circuits can use the coupler to control large current and voltages with low-voltage logic levels.

TRANSISTORS

3-64. Transistors are semiconductor devices with three or more terminals. The operation of normal transistors has already been covered. However, there are several transistors with special properties that should be explained. As with diodes, covering all the developments in the transistor field would be impossible. The unijunction transistor and the field-effect transistor will be covered because of their widespread application in Army equipment.

The Unijunction Transistor

3-65. The UNIJUNCTION TRANSISTOR, originally called a double-based diode, is a three-terminal, solid state device that has several advantages over conventional transistors. It is very stable over a wide range of temperatures and allows a reduction of components when used in the place of conventional transistors. Figure 3-38 shows a comparison of a conventional transistor and a UJT. View (A) shows a circuit using conventional transistors and view (B) is the same circuit using the UJT. As you can see, the UJT circuit has fewer components. Reducing the number of components reduces the cost, size, and probability of failure.

3-66. The physical appearance of the UJT is identical to that of the common transistor (see Figure 3-39). Both have three leads and the same basic shape. The tab on the case indicates the emitter on both devices. The difference in the two is that the transistor has a collector (C) (view A) while the UJT has a second base instead of a collector (view B).

3-67. The block diagram (see Figure 3-40) shows that the lead differences are even more pronounced. Unlike the transistor, the UJT has only one PN junction. The area between base 1 and base 2 acts as a resistor when the UJT is properly biased. A conventional transistor needs a certain bias level between the emitter, base, and collector for proper

conduction. The same principle is true for the UJT; it needs a certain bias level between the emitter and base 1 and also between base 1 and base 2 for proper conduction.

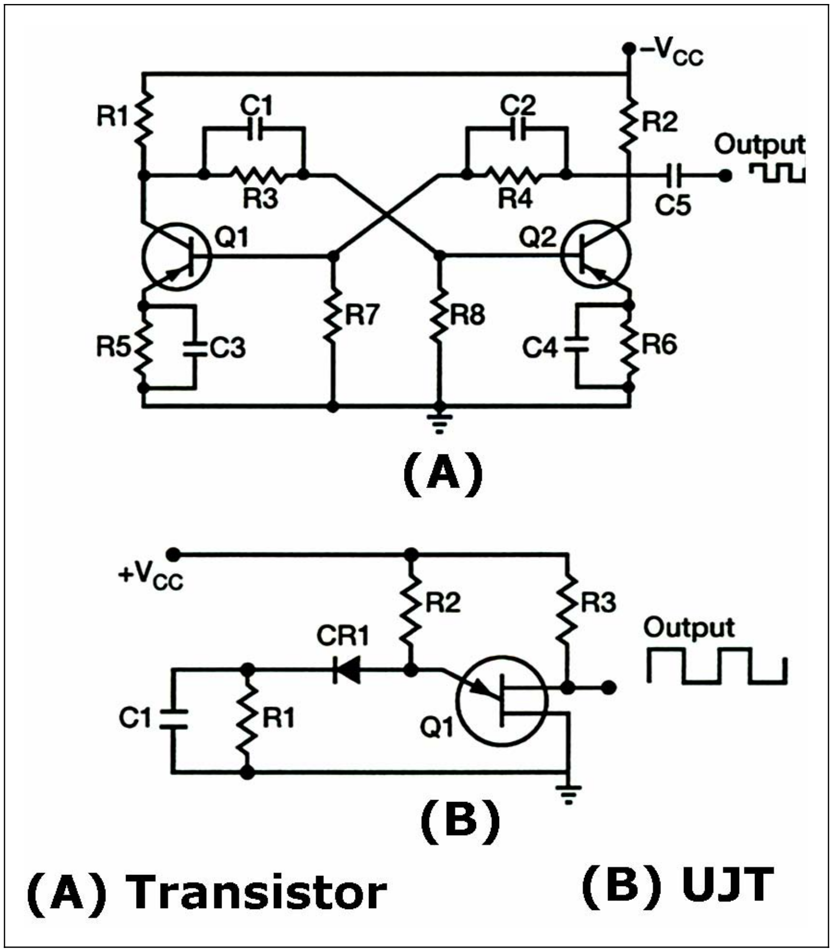


Figure 3-38. Comparison of Conventional Transistor and UJT Circuits

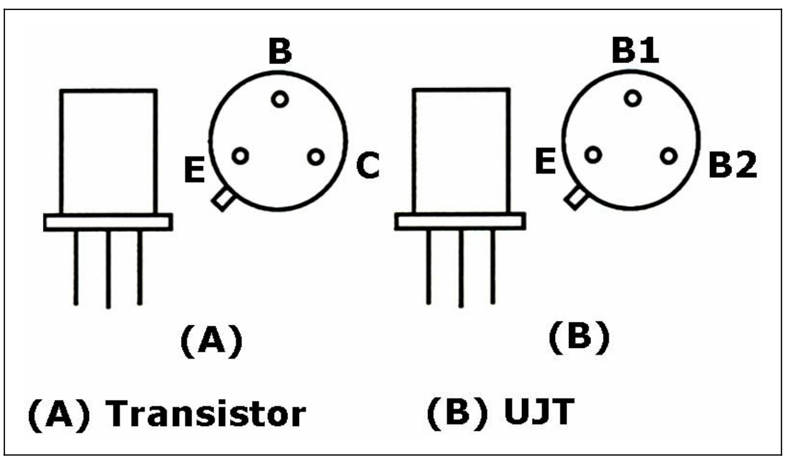


Figure 3-39. Transistor and UJT

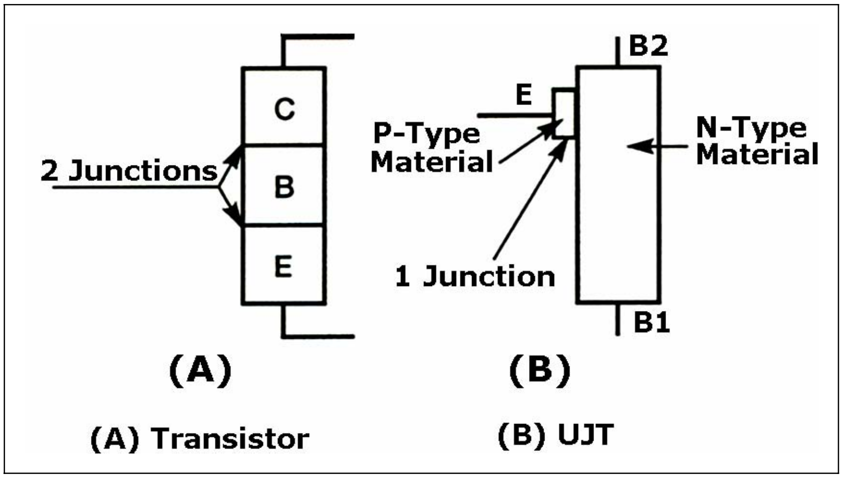


Figure 3-40. Transistor and UJT Structure

3-68. Figure 3-41, view (A), shows the normal bias arrangement for the UJT. A positive 10 volts is placed on base 2 and a ground on base 1. The area between base 1 and base 2 then acts as a resistor. If a reading were taken between base 1 and base 2, the meter would indicate the full 10 volts (see Figure 3-41, view (B)). Theoretically, if one meter lead were connected to base 1 and the other lead to some point between base 1 and base 2, the meter could read some voltage less than 10 volts (Figure 3-42, view (A) shows this concept). View (B) also shows the voltage levels at different points between the two bases. The sequential rise in voltage is called a voltage gradient.

3-69. The emitter of the UJT can be viewed as the wiper arm of a variable resistor. If the voltage level on the emitter is more positive than the voltage gradient level at the emitter-base material contact point, then the UJT is forward biased. The UJT will conduct heavily (almost a short circuit) from base 1 to the emitter. The manufacturer fixes the emitter in position. The level of the voltage gradient therefore depends upon the amount of bias voltage (see Figure 3-43).

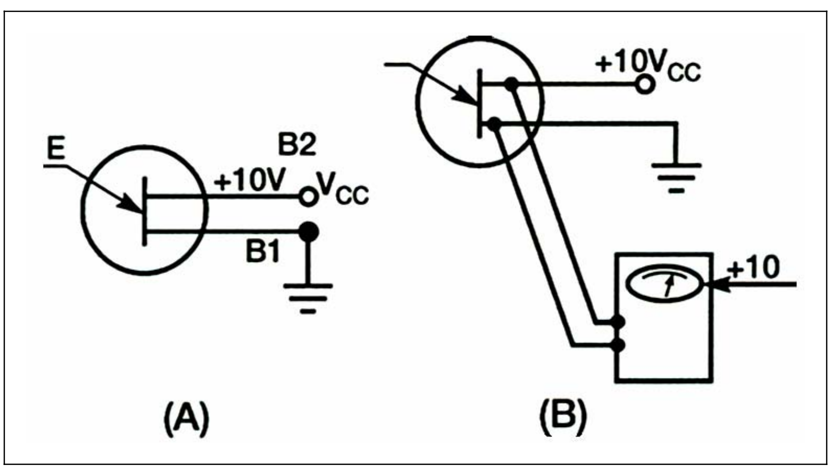


Figure 3-41. UJT Biasing

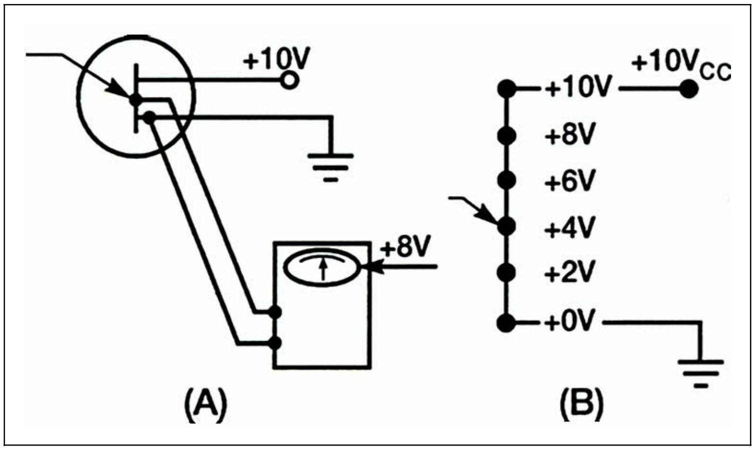


Figure 3-42. UJT Voltage Gradient

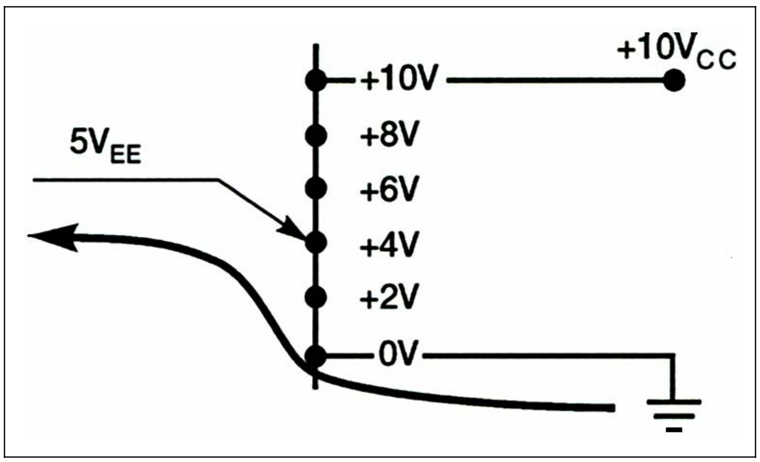


Figure 3-43. Forward Bias Point on UJT Voltage Gradient

3-70. If the voltage level on the emitter is less positive than the voltage gradient opposite the emitter, the UJT is then reverse biased. No current will flow from base 1 to the emitter. However, a small current, called reverse current, will flow from the emitter to base 2. The reverse current is caused by the impurities used in the construction of the UJT and is in the form of minority carriers.

3-71. More than forty distinct types of UJTs are presently in use. One of the most common applications is in switching circuits. They are also used extensively in oscillators and wave shaping circuits.

Field-effect Transistors

3-72. Although it has brought about a revolution in the design of electronic equipment, the bipolar (PNP/NPN) transistor still has one very undesirable characteristic. The low input impedance associated with its base-emitter junction causes problems in matching impedances between interstage amplifiers.

3-73. For years, scientists searched for a solution that would combine the high input impedance of the vacuum tube with the many other advantages of the transistor. The result of this research is the FIELD-EFFECT TRANSISTOR. In contrast to the bipolar transistor, which uses bias current between base and emitter to control conductivity, the FET uses

voltage to control an electrostatic field within the transistor. Since the FET is voltage-controlled, much like a vacuum tube, it is sometimes called the "solid state vacuum tube."

3-74. The elements of one type of FET, the junction field-effect transistor type, are compared with the bipolar transistor and the vacuum tube (see Figure 3-44). As the figure shows, the JFET is a three-element device comparable to the other two. The "gate" element of the JFET corresponds very closely in operation to the base of the transistor and the grid of the vacuum tube. The "source" and "drain" elements of the JFET correspond to the emitter and collector of the transistor and to the cathode and plate of the vacuum tube.

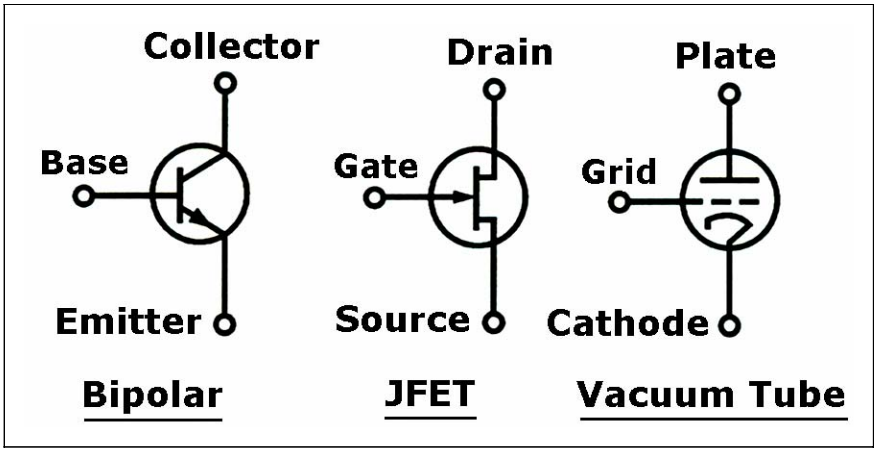


Figure 3-44. Comparison of JFET, Transistor, and Vacuum Tube

3-75. Figure 3-45 shows the construction of a JFET. A solid bar, made either of N-type or P-type material, forms the main body of the device. Diffused into each side of this bar are two deposits of material of the opposite type from the bar material, which form the "gate." The portion of the bar between the deposits of gate material is of a smaller cross section than the rest of the bar and forms a "channel" connecting the source and the drain. Figure 3-45 also shows a bar of N-type material and a gate of P-type material. Since the material in the channel is N-type, the device is called an N-channel JFET.

3-76. In a P-channel JFET, the channel is made of P-type material and the gate of N-type material. Figure 3-46 shows the schematic symbols for the two types of JFET being compared with those of the NPN and PNP bipolar transistor. Like the bipolar transistor types, the two types of JFET differ only in the configuration of bias voltages required and in the direction of the arrow within the symbol. Just as it does in transistor symbols, the arrow in a JFET symbol always points towards the N-type material. Therefore, the symbol of the N-channel JFET shows the arrow pointing towards the drain/source channel, while the P-channel symbol shows the arrow pointing away from the drain/source channel towards the gate.

3-77. The key to FET operation is the effective cross-sectional area of the channel, which can be controlled by variations in the voltage applied to the gate. This is demonstrated in Figures 3-47, 3-48, and 3-49.

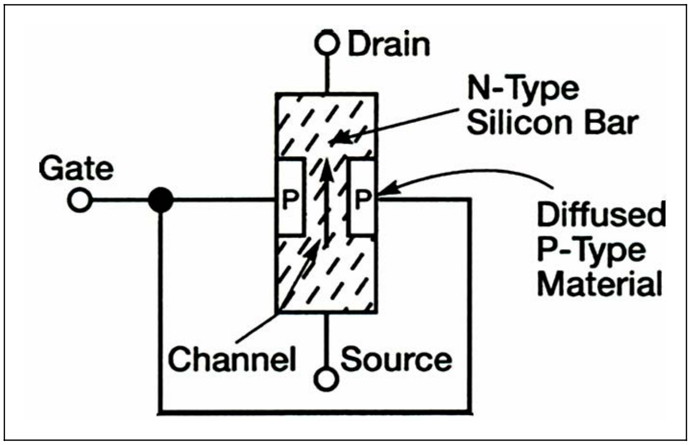


Figure 3-45. JFET Structure

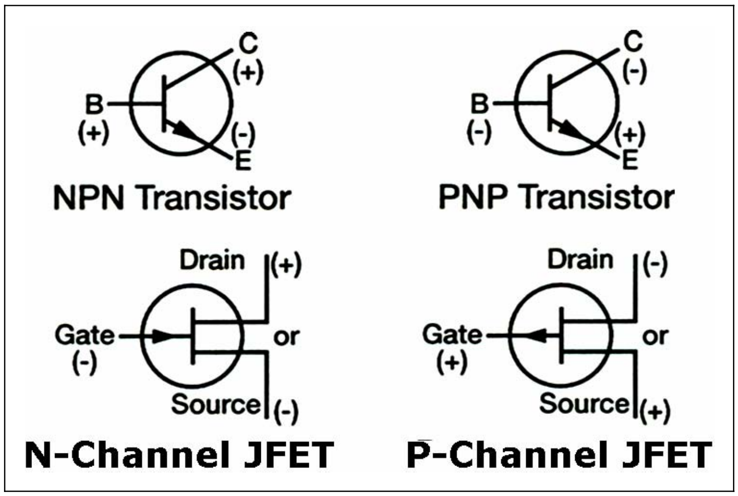


Figure 3-46. Symbols and Bias Voltages for Transistors and JFET

3-78. Figure 3-47 shows how the JFET operates in a zero gate bias condition. Five volts are applied across the JFET so that current flows through the bar from source to drain, as indicated by the arrow. The gate terminal is tied to ground. This is a zero gate bias condition. In this condition, a typical bar represents a resistance of about 500 ohms. A milliammeter, connected in series with the drain lead and DC power, indicates the amount of current flow. With a drain supply (V_{DD}) of 5 volts, the milliammeter gives a drain current (I_D) reading of 10 milliamperes. The voltage and current subscript letters (V_{DD}, I_D) used for a FET correspond to the elements of the FET just as they do for the elements of transistors.

3-79. In Figure 3-48, a small reverse-bias voltage is applied to the gate of the JFET. A gate-source voltage (V_{GG}) of negative 1 volt applied to the P-type gate material causes the junction between the P- and N-type material to become reverse biased. Just as it did in the varactor diode, a reverse-bias condition causes a “depletion region” to form around the PN junction of the JFET. Since this region has a reduced number of current carriers, the effect of reverse biasing is to reduce the effective cross-sectional area of the “channel.” This reduction in area increases the source-to-drain resistance of the device and decreases current flow.

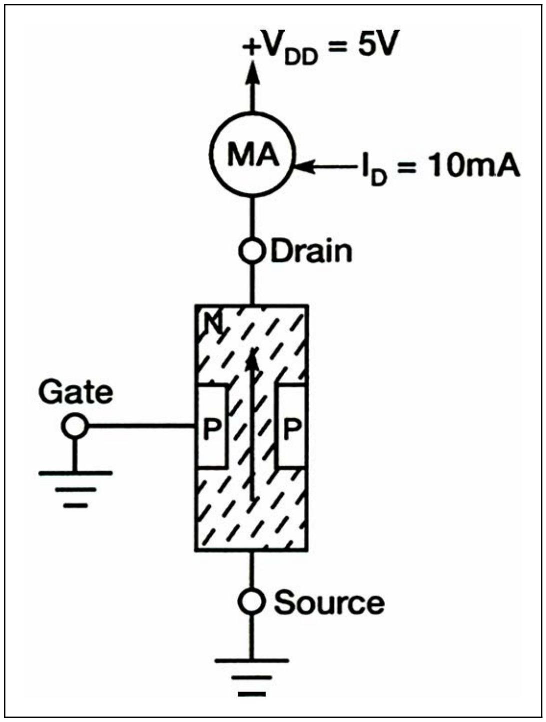


Figure 3-47. JFET Operation With Zero Gate Bias

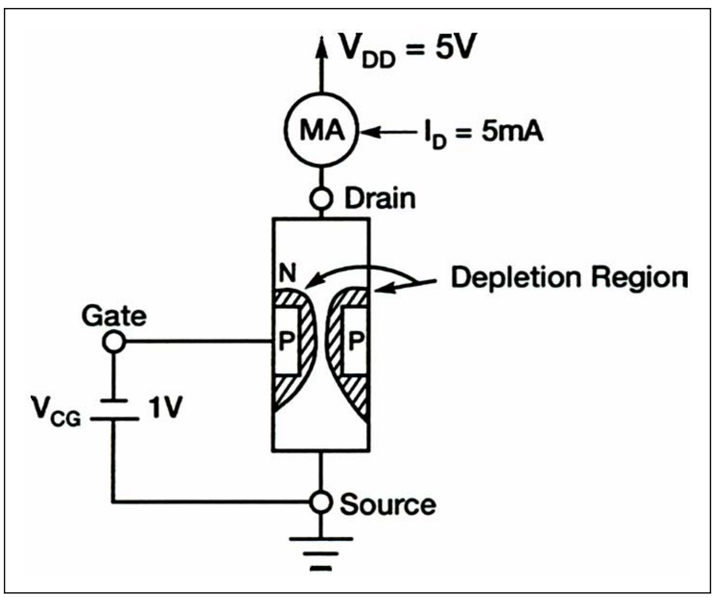


Figure 3-48. JFET With Reverse Bias

3-80. The application of a large enough negative voltage to the gate will cause the depletion region to become so large that conduction of current through the bar stops altogether. The voltage required to reduce drain current (I_D) to zero is called “pinch-off” voltage and is comparable to “cut-off” voltage in a vacuum tube. In Figure 3-48, the negative 1 volt applied, although not large enough to completely stop conduction, has caused the drain current to decrease markedly (from 10 milliamperes under zero gate bias conditions to 5 milliamperes). Calculation shows that the 1-volt gate bias has also

increased the resistance of the JFET (from 500 ohms to 1 kilohm). In other words, a 1 volt change in gate voltage has doubled the resistance of the device and cut current flow in half.

3-81. However, these measurements only show that a JFET operates in a manner similar to a bipolar transistor, even though the two are constructed differently. Remember, the main advantage of an FET is that its input impedance is significantly higher than that of a bipolar transistor. The higher input impedance of the JFET under reverse gate bias conditions can be seen by connecting a microammeter in series with the gate-source voltage (V_{GG}) (see Figure 3-49).

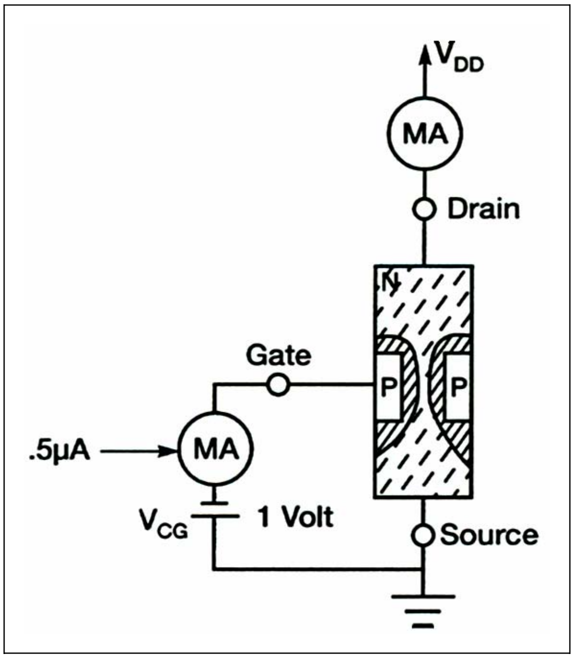


Figure 3-49. JFET Input Impedance

3-82. With a V_{GG} of 1 volt, the microammeter reads .5 microamps. Applying Ohm's law ($1V \div .5\mu A$) shows that this very small amount of current flow results in a very high input impedance (about 2 megohms). By contrast, a bipolar transistor in similar circumstances would require higher current flow (for example, .1 to -1 mA), resulting in a much lower input impedance (about 1000 ohms or less). The higher input impedance of the JFET is possible because of the way reverse-bias gate voltage affects the cross-sectional area of the channel.

3-83. The preceding example of JFET operation uses an N-channel JFET. However, a P-channel JFET operates on identical principles. Figure 3-50 shows the differences between the two types.

3-84. Since the materials used to make the bar and the gate is reversed, source voltage potentials must also be reversed. The P-channel JFET therefore requires a positive gate voltage in order to be reverse biased, and current flows through it from drain to source.

3-85. Figure 3-51 shows a basic common-source amplifier circuit containing an N-channel JFET. The characteristics of this circuit include high input impedance and a high voltage gain. The function of the circuit components in Figure 3-51 is very similar to those in a triode vacuum tube common-cathode amplifier circuit. C1 and C3 are the input and

output coupling capacitors. R1 is the gate return resistor and functions much like the grid return resistor in a vacuum tube circuit. R1 prevents unwanted charge buildup on the gate by providing a discharge path for C1. R2 and C2 provide source self-bias for the JFET, which operates like cathode self-bias. R3 is the drain load resistor, which acts like the plate or collector load resistor.

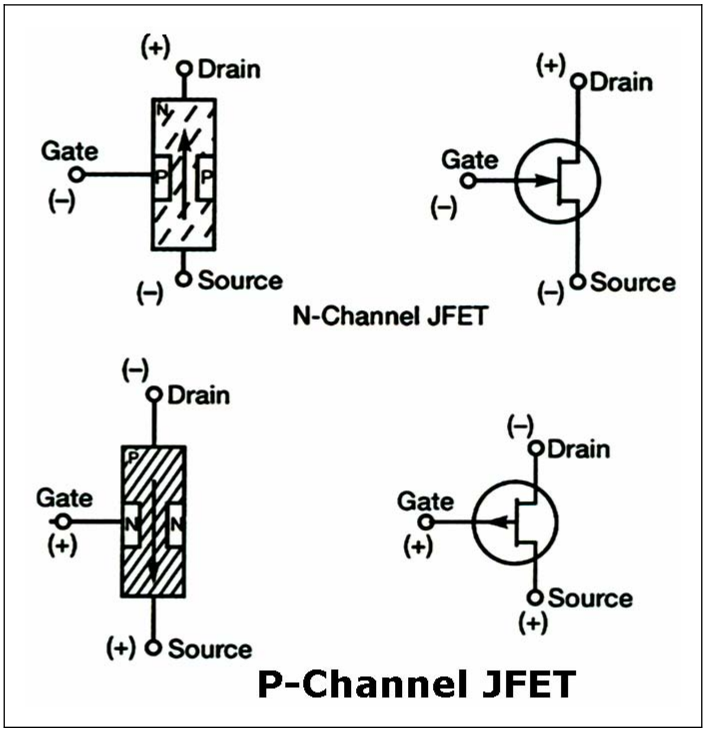


Figure 3-50. JFET Symbols and Bias Voltages

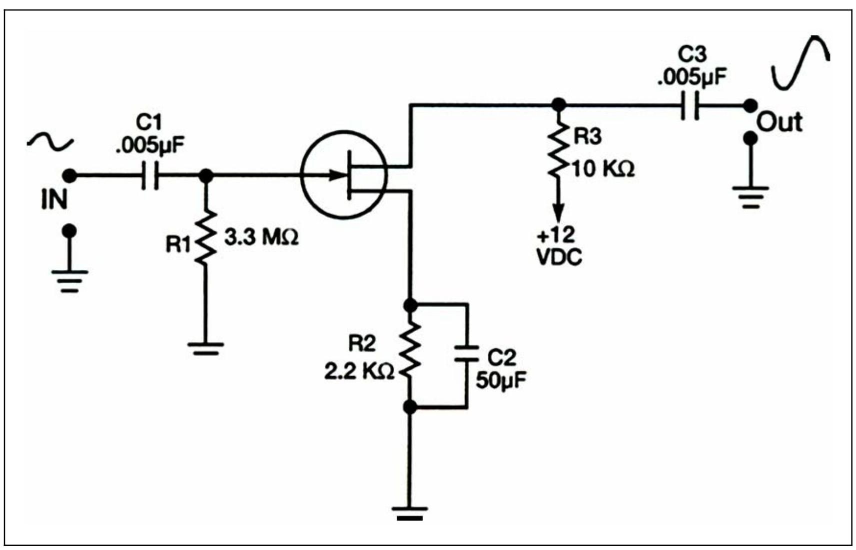


Figure 3-51. JFET Common Source Amplifier

3-86. The phase shift of 180 degrees between input and output signals are the same as that of common-cathode vacuum tube circuits and CE transistor circuits. The reason for the

phase shift can easily be seen by observing the operation of the N-channel JFET. On the positive alternation of the input signal, the amount of reverse bias on the P-type gate material is reduced, thereby increasing the effective cross-sectional area of the channel and decreasing source-to-drain resistance. When resistance decreases, current flow through the JFET increases. This increase causes the voltage drop across R3 to increase, which in turn causes the drain voltage to decrease. On the negative alternation of the cycle, the amount of reverse bias on the gate of the JFET is increased and the action of the circuit is reversed. The result is an output signal that is an amplified 180-degree-out-of-phase version of the input signal.

3-87. A second type of FET has been introduced in recent years that have some advantages over the JFET. This device is the metal oxide semiconductor field-effect transistor. The MOSFET has an even higher input impedance (10 to 100 million megohms) than the FET. Therefore, the MOSFET is even less of a load on preceding circuits. The extremely high input impedance, combined with a high gain factor, makes the MOSFET a highly efficient input device for RF and IF amplifiers and mixers and for many types of test equipment.

3-88. The MOSFET is normally constructed so that it operates in one of two basic modes (the depletion mode or the enhancement mode). The depletion mode MOSFET has a heavily doped channel and uses reverse bias on the gate to cause a depletion of current carriers in the channel. The JFET also operates this way. The enhancement mode MOSFET has a lightly doped channel and uses forward bias to enhance the current carriers in the channel. A MOSFET can be constructed that will operate in either mode depending upon what type of bias is applied, thereby allowing a greater range of input signals.

3-89. In addition to the two basic modes of operation, the MOSFET, like the JFET, is either of the P-channel type or the N-channel type. Each type has the following four elements:

- Gate.
- Drain.
- Substrate.
- Source.

Figure 3-52 (views (A), (B), (C), and (D)) shows the schematic symbols for the four basic variations of the MOSFET.

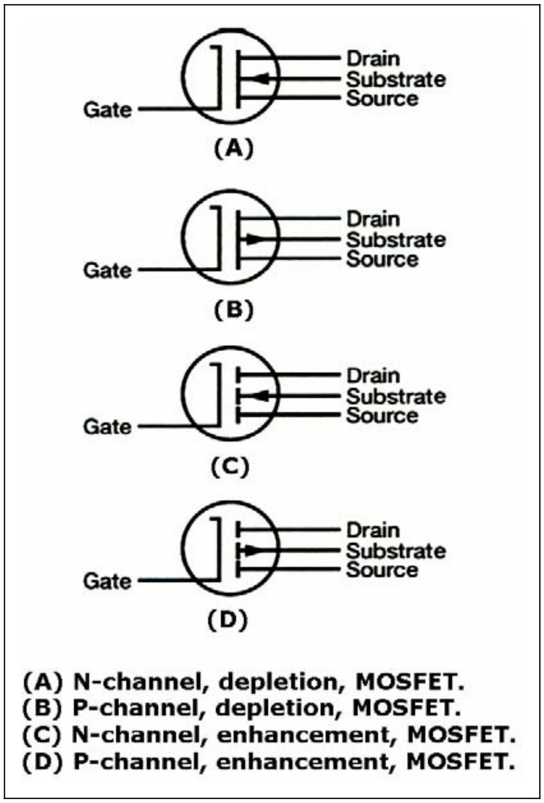


Figure 3-52. MOSFET Symbols

3-90. Figure 3-53 shows the construction of an N-channel MOSFET. Heavily doped N-type regions (indicated by the N+) are diffused into a P-type substrate or base. A channel of regular N-type material is diffused between the heavily doped N-type regions. A metal oxide-insulating layer is then formed over the channel and a metal gate layer is deposited over the insulating layer. There is no electrical connection between the gate and the rest of the device. This construction method results in the extremely high input impedance of the MOSFET. Another common name for the device, derived from the construction method, is the insulated gate field-effect transistor.

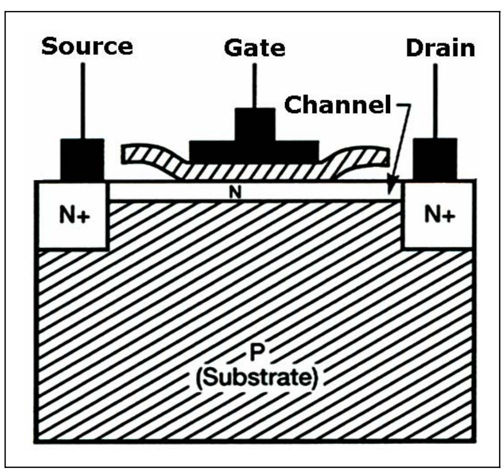


Figure 3-53. Construction of an N-channel MOSFET

3-91. The operation of the MOSFET, or IGFET, is basically the same as the operation of the JFET. The current flow between the source and drain can be controlled by using either one of two methods or by using a combination of the two methods. In one method the drain voltage controls the current when the gate potential is at zero volts. A voltage is applied to the gate in the second method. The gate voltage that affects the current flow in the channel by either depleting or enhancing the number of current carriers available forms an electric field. Remember, a reverse bias applied to the gate depletes the carriers and a forward bias enhances the carriers. The polarity of the voltages required to forward or reverse bias a MOSFET depends upon whether it is of the P-channel type or the N-channel type. Figure 3-54, views (A), (B), and (C) shows the effects of reverse-bias voltage on a MOSFET designed to operate in the depletion mode. The amount of reverse bias applied has a direct effect on the width of the current channel and thereby, the amount of drain current (I_D).

3-92. Figure 3-55 shows the effect of forward bias on an enhancement mode N-channel MOSFET. In this case, a positive voltage applied to the gate increases the width of the current channel and the amount of drain current (I_D).

3-93. Another type of MOSFET is the induced-channel type MOSFET. Unlike the MOSFETs covered so far, the induced-channel type has no actual channel between the source and the drain. The induced channel MOSFET is constructed by making the channel of the same type material as the substrate, or the opposite of the source and the drain material (see Figure 3-56). The figure also shows that the source and the drain are of P-type material and the channel and the substrate are of N-type material.

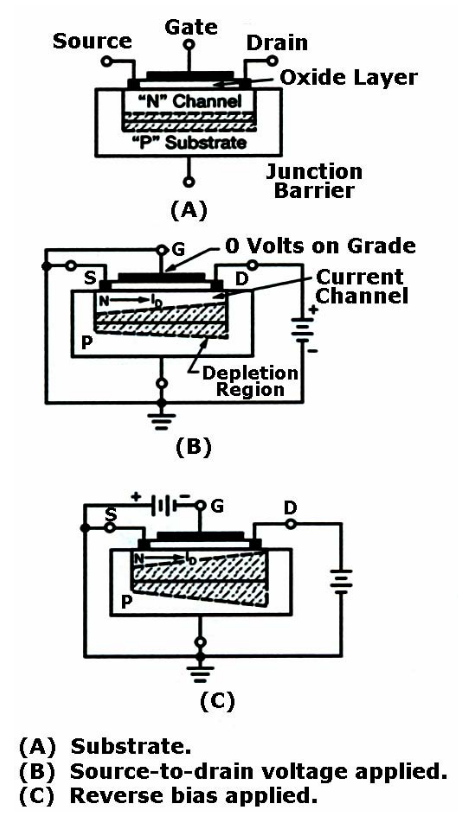


Figure 3-54. Effects of Reverse-bias Voltage (MOSFET in Depletion Mode)

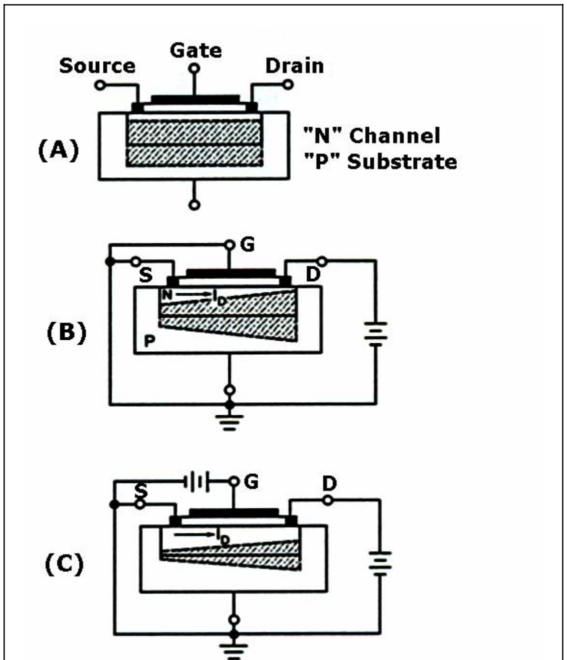


Figure 3-55. Effects of Forward-bias (N-channel MOSFET in Enhancement Mode)

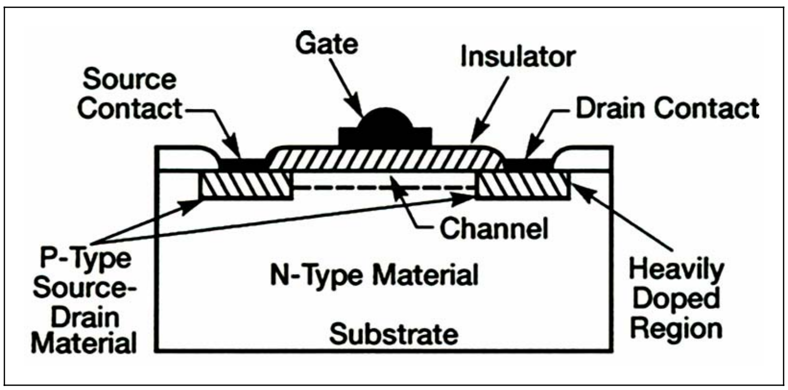


Figure 3-56. Induced Channel MOSFET Construction

3-94. The induced-channel MOSFET conducts from source to drain by the electric field that is created when a voltage is applied to the gate. For example, assume that a negative voltage is applied to the MOSFET in Figure 3-56. The effect of the negative voltage modifies the conditions in the substrate material. As the gate builds a negative charge, free electrons are repelled, forming a depletion region. Once a certain level of depletion has occurred (determined by the composition of the substrate material), any additional gate bias attracts positive holes to the surface of the substrate. When enough holes have accumulated at the surface channel area, the channel changes from an N-type material to a P-type material (since it now has more positive carriers than negative carriers). At this point the channel is considered to be inverted and a P-type inversion layer or channel now connects the two P-type regions at the source and the drain. As with the MOSFET, the gate

signal determines the amount of current flow through the channel as long as the source and drain voltages remain constant. When the gate voltage is at zero, essentially no current flows since a gate voltage is required to form a channel.

3-95. The MOSFETs discussed so far have been single-gate MOSFETs. Another type of MOSFET is the dual-gate type (see Figure 3-57). The gates in a dual-gate MOSFET can be compared to the grids in a multi-grid vacuum tube. Since the substrate has been connected directly to the source terminal, the dual-gate MOSFET still has only four leads (one each for source and drain and two for the gates). Either gate can control conduction independently, making this type of MOSFET a truly versatile device.

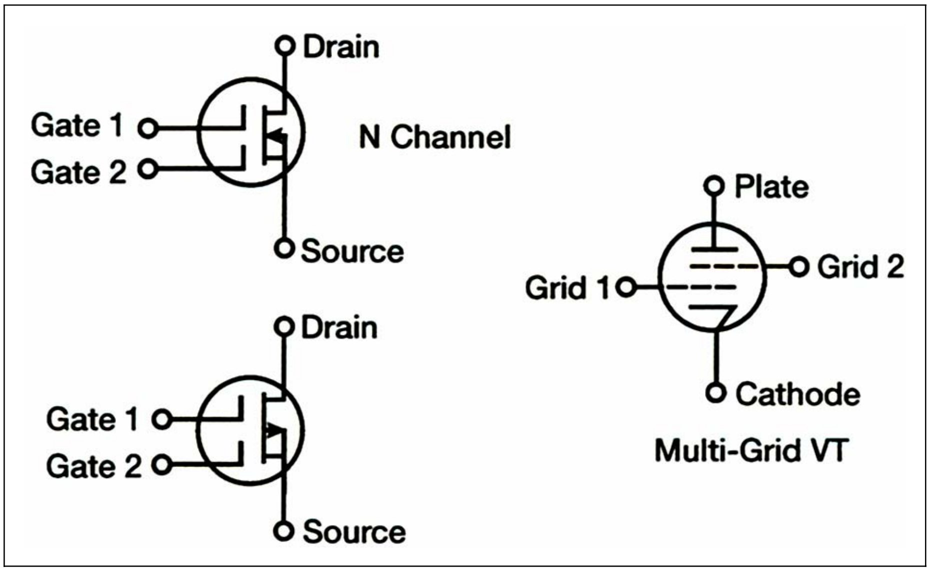


Figure 3-57. Dual Gate MOSFET

3-96. One problem with both the single- and dual-gate MOSFET is that the oxide layer between gate and channel can be destroyed very easily by ordinary static electricity. Replacement MOSFETs come packaged with their leads shorted together by a special wire loop or spring to avoid accidental damage. The rule to remember with these shorting springs is that they must not be removed until after the MOSFET has been soldered or plugged into a circuit. Figure 3-58 shows one such shorting spring.

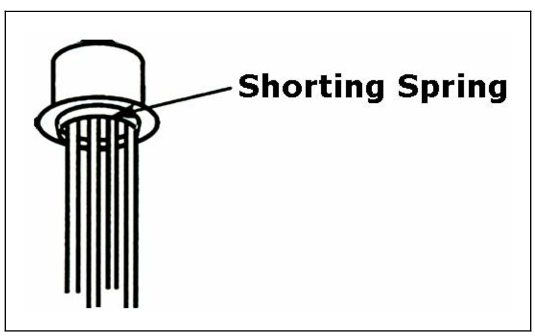
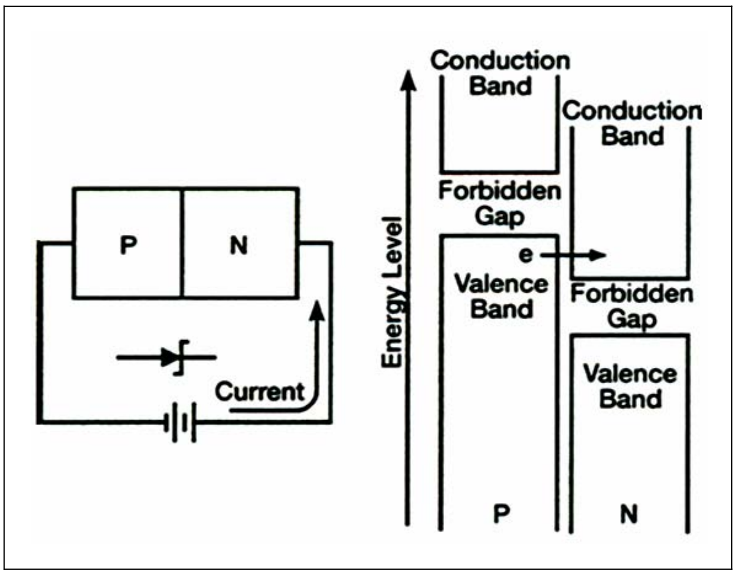


Figure 3-58. MOSFET Shorting Spring

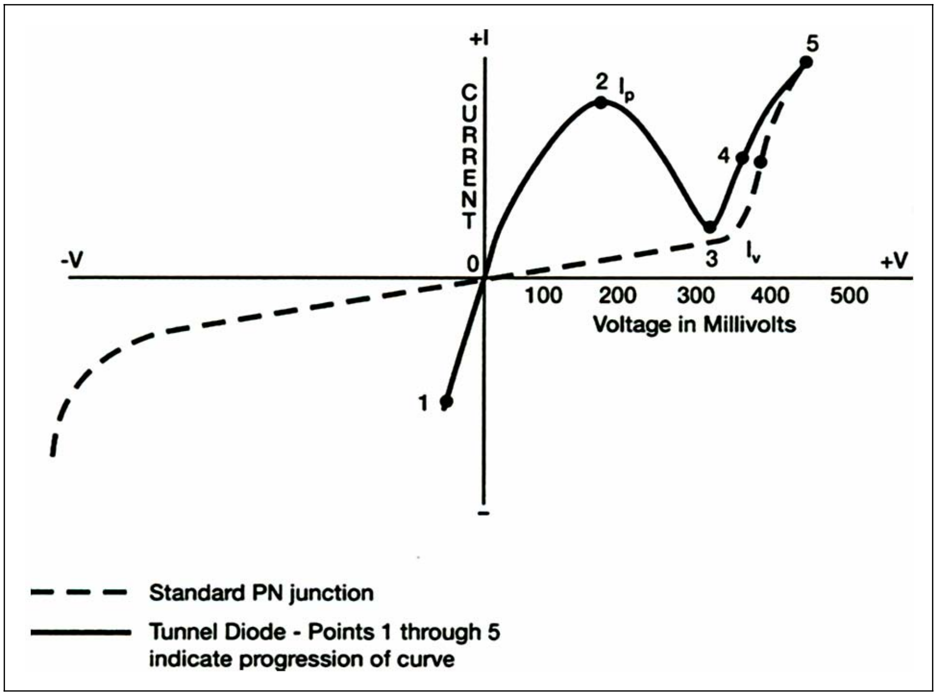
SUMMARY

3-97. Now that we have completed this chapter, the following is a short review of the more important points. Answer the check-on-learning questions, found after the summary, to determine how much you have learned from this chapter.

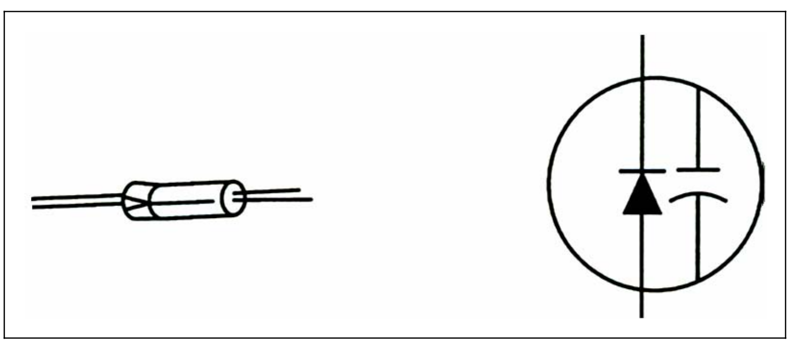
ZENER DIODE **-** a PN junction that is designed to operate in the reverse-bias breakdown mode. When the applied voltage reaches the breakdown point, the Zener diode, for all practical purposes, becomes a short circuit. The reverse bias and breakdown mode of operation causes the Zener diode to conduct with (in the direction of) the arrow in the symbol. Two theories are used to explain the breakdown action of Zener diodes. The ZENER EFFECT explains the breakdown of diodes below *S* volts. The heavy doping used in these diodes allows the valence band of one material to overlap the energy level of the conduction band of the other material. This situation allows electrons to tunnel across the PN junction at the point where the two energy bands overlap. Zener diodes that operate above 5 volts are explained by the AVALANCHE EFFECT, in which free electrons colliding with bound electrons cause an ever-increasing number of free current carriers in a multiplying action. The Zener diode is used primarily as a voltage regulator in electronic circuits.



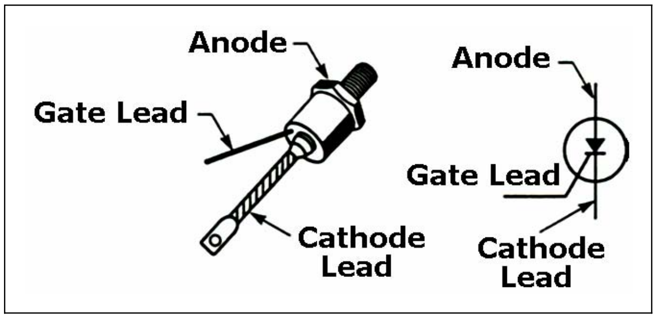
TUNNEL DIODE **-** a heavily doped PN junction that exhibits negative resistance over part of its range of operation. The heavy doping causes the tunnel diode to have a very narrow depletion region and also causes the valence band of one of the semiconductor materials to overlap the energy level of the conduction band of the other semiconductor material. At the energy overlap point, electrons can cross from the valence band of one material to the conduction band of the other material without acquiring any additional energy. This action is called tunneling. Tunnel diodes are used as amplifiers, oscillators, and high-speed switching devices.



VARACTOR **-** a diode that exhibits the characteristics of a variable capacitor. The depletion region at the PN junction acts as the dielectric of a capacitor and is caused to expand and contract by the voltage applied to the diode. This action increases and decreases the capacitance. Varactors are used in tuning circuits and can be used as high-frequency amplifiers.

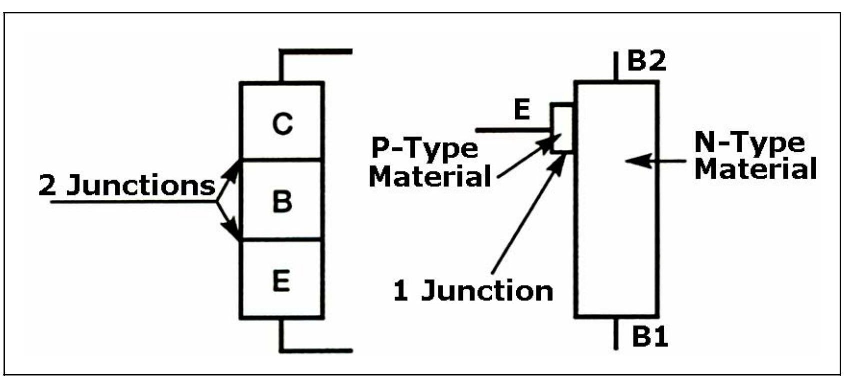


SILICON CONTROLLED RECTIFIER **-** a four-element, solid state device that combines characteristics of diodes and transistors. A signal must be applied to the gate to cause the SCR to conduct. When the proper gate signal is applied, the SCR conducts or "fires" until the bias potential across the device drops below the minimum required sustaining current flow. Removal of the gate signal does not shut off the SCR. In fact, the gate signal is often a very narrow voltage pulse or trigger. The SCR is ideal for use in situations where a small, low-power gate can be used to turn on larger current, such as those found in rectifier and switching circuits. SCRs are used extensively in power supply circuits as rectifiers.



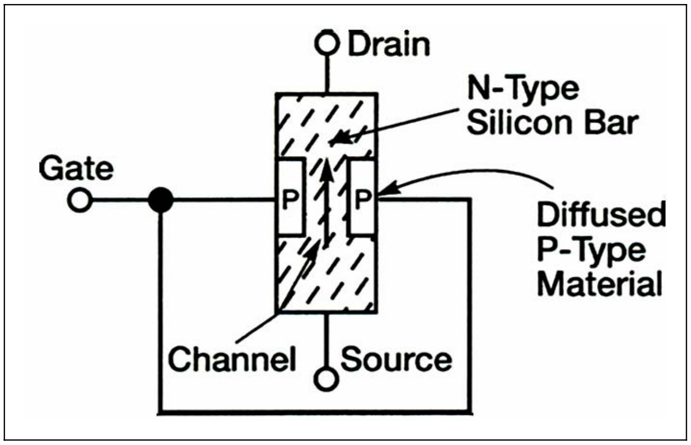
OPTOELECTRONIC DEVICES – the two basic types are light producers or light users. The LED is the most widely used light-producing device. When the LED is forward biased it emits energy in the form of light. LEDs are used in several configurations as digital equipment readout displays. The PHOTODIODE, the PHOTOTRANSISTOR, and the PHOTOCELL are all devices that use light to modify the conduction through them. The SOLAR CELL uses light to produce voltage.

UNIJUNCTION TRANSISTOR **-** a three-terminal, solid state device with only one PN junction. The area between base 1 and base 2 of the UJT acts as a variable resistor. The emitter of the UJT acts as the wiper arm. The sequential rise in voltage between the bases is called a voltage gradient. The UJT conducts when the emitter is more positive than the voltage gradient at the emitter/base contact point. There are many variations of the UJT which are used in switching circuits, oscillators, and wave-shaping circuits.



FIELD-EFFECT TRANSISTOR - combines the high input impedance of the vacuum tube with all the other advantages of the transistor. The elements of the FET are the gate, source, and drain which are comparable to the base, emitter, and collector of a standard transistor.

JUNCTION FIELD-EFFECT TRANSISTOR - is made of a solid bar of either P- or N-semiconductor material, and the gate is made of the opposite type material. The FET is called P-channel or N-channel depending upon the type of material used to make the bar between the source and drain. Voltage applied to the gate controls the width of the channel and consequently controls the current flow from the source to the drain. The JFET is normally operated with reverse bias that controls the channel width by increasing or decreasing the depletion region.



MOSFET - is a FET that has even higher input impedances than the JFET because the gate of the MOSFET is completely insulated from the rest of the device. The MOSFET operates in either the depletion mode or the forward-bias enhancement mode and can be either N-channel or P-channel. The induced-channel and the dual-gate MOSFETs are variations of the basic MOSFET.

CHAPTER 3
CHECK-ON-LEARNING QUESTIONS

When you are satisfied that you have answered every question to the best of your ability, check your answers using Appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. In a reverse-biased PN junction, the presence of what causes a small leakage current?

2. The action of a PN junction during breakdown can be explained by what two theories?

3. Which breakdown theory explains the action that takes place in a heavily doped PN junction with a reverse bias of less than 5 volts?

4. What is the name of the gap (where electrons must cross) between the valence band energy level and the conduction band energy level?

5. During Avalanche effect breakdown, what limits current flow through the diode?

6. For what are Zener diodes mostly used?

7. What is the name of the theory where an electron crosses a junction without having sufficient energy?

8. What is the net current flow when current carriers move across the depletion region due to thermal energy?

9. What is the most important and widely used characteristic of the tunnel diode?

10. What is the name of the region that is void of positive and negative charged current carriers surrounding the P and N materials?

11. To what is the size of the depletion region in a varactor diode related?

12. When a PN junction is forward biased, what happens to the depletion region?

13. What is one advantage of the varactor?

14. What is the basic purpose of the SCR?

15. The SCR is made up of how many layers of semiconductor material?

16. The SCR turns off automatically when what power source is used?

17. The triac is similar in operation to what device?

18. When used for AC current control, during which alternation of the AC cycle does the triac control current flow?

19. What type of bias is required to cause an LED to produce light?

20. What is the LED operating voltage when forward bias?

21. What type voltage do you apply to the seven-segment display to form numbers?

22. What is the resistance level of a photodiode in total darkness?

23. What type of bias is required for proper operation of a photodiode?

24. What is a typical light-to-dark resistance ratio for a photocell?

25. What device converts light energy into electrical energy?

26. The UJT has how many PN junctions?

27. The area between base 1 and base 2 of the UJT will act as a what when placing a positive 10 volts on base 2 and a ground on base 1?

28. What is called the sequential rise in voltage between the two bases of the UJT?

29. Who fixes the emitter in position?

30. What does the FET use to control an electrostatic field within the transistor?

31. The base of a transistor serves a purpose similar to what element of the FET?

32. What are the two types of JFET?

33. What is the key to FET operation?

34. How many volts are applied across the JFET so that current flows through the bar from source to drain?

35. What is it called when voltage is required to reduce drain current to zero?

36. What is the main advantage of an FET over a bipolar transistor?

37. What does a P-channel JFET require in order to be reverse biased?

38. When compared to the FET, what is the input impedance of the MOSFET?

39. What are the two basic modes that the MOSFET is constructed to operate?

40. What are the four elements of the MOSFET?

41. The polarity of the voltages required to forward or reverse bias a MOSFET depends on what?

42. What is the purpose of the spring or wire around the leads of a new MOSFET?

Chapter 4
Solid State Power Supplies

LEARNING OBJECTIVES

Learning objectives serve as a preview of the information you are expected to learn in this chapter. The comprehensive check-on-learning questions, found at the end of the chapter, are based on the objectives. Upon completion of this chapter, you will be able to perform the following learning objectives:

- Identify the various sections of a power supply.
- State the purpose of each section of a power supply.
- Describe the operation of the power supply from both a whole unit standpoint and from a subunit standpoint.
- Describe the purpose of the various types of rectifier circuits used in power supplies.
- Describe the purpose of the various types of filter circuits used in power supplies.
- Describe the operation of the various voltage and current regulators in a power supply.
- Describe the operation of the various types of voltage multipliers.
- Trace the flow of AC and DC in a power supply from the AC input to the DC output on a schematic diagram.
- Identify faulty components through visual checks.
- Identify problems within specific areas of a power supply by using a logical isolation method of troubleshooting.
- Apply safety precautions when working with electronic power supplies.

INTRODUCTION TO POWER SUPPLIES

4-1. In today's Army, all electronic equipment requires a power supply. Because of new technology and equipment, the solid state power supply must also be explained. The discovery of the silicon diode and other solid state components made possible the reduction in size and the increase in reliability of electronic equipment. This is especially important in mobile equipment where space and accessibility to spare parts are a major concern. In this chapter, you will learn about the individual sections of the power supply, their components, and the purpose of each within the power supply.

THE BASIC POWER SUPPLY

4-2. Figure 4-1, view (A) shows the block diagram of a basic power supply. Most power supplies are made up of the following four basic sections:

- Transformer.
- Rectifier.
- Filter.
- Regulator.

4-3. Figure 4-1, view (B) shows the first section as the TRANSFORMER. The transformer steps up or steps down the input line voltage and isolates the power supply from the power line. The RECTIFIER section converts the AC input signal to a pulsating DC voltage. However, you will see later on in this chapter that the pulsating DC is not desirable. For this reason, a FILTER section is used to convert pulsating DC to a purer, more desirable form of DC voltage. The REGULATOR section does just what the name implies, it maintains the output of the power supply at a constant level in spite of large changes in load current or input line voltages.

4-4. Now that you know what each section does, let us trace an AC signal through the power supply. At this point you need to see how this signal is altered within each section of the power supply. You will see later how these changes take place. In Figure 4-1, view (B), an input signal of 115 volts AC is applied to the primary of the transformer. The transformer is a step-up transformer with a turns ratio of 1:3. You can calculate the output for this transformer by multiplying the input voltage by the ratio of turns in the primary to the ratio of turns in the secondary. Therefore, 115 volts AC x 3 = 345 volts AC (peak-to-peak) at the output. Since each diode in the rectifier section conducts for 180 degrees of the 360-degree input, the output of the rectifier will be one-half, or approximately 173 volts of pulsating DC. The filter section, a network of resistors, capacitors, or inductors; controls the rise and fall time of the varying signal. Consequently, the signal remains at a more constant DC level. You will see the filter process more clearly in the discussion of the actual filter circuits. The output of the filter is a signal of 110 volts DC, with AC ripple riding on the DC. The reason for the lower voltage (average voltage) will be explained later in the chapter. The regulator maintains its output at a constant 110-volt DC level, which is used by the electronic equipment (more commonly called the load).

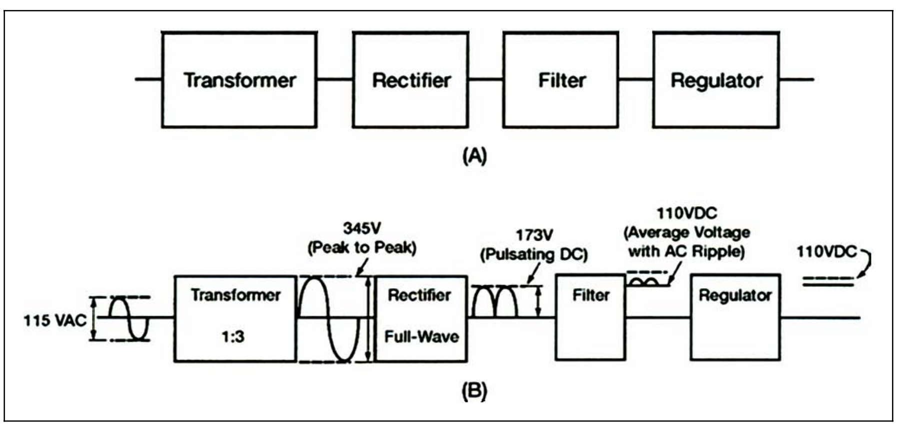


Figure 4-1. Block Diagram of a Basic Power Supply

THE POWER TRANSFORMER

4-5. In some cases a power supply may not use a transformer. Therefore, the power supply would be connected directly to the source line voltage. This type of connection is primarily used because it is economical. However, unless the power supply is completely insulated, it presents a dangerous shock hazard to anyone who comes in contact with it. When a transformer is not being used, the return side of the AC line is connected to the metal chassis. Use a transform to remove this potential shock hazard and to have the option of stepping up or stepping down the input voltage to the rectifier.

4-6. Figure 4-2 shows the schematic diagram for the following:

- View (A) shows a STEP-UP transformer.
- View (B) shows a STEP-DOWN transformer.
- View (C) shows a STEP-UP, CENTER-TAPPED transformer.

Only the center-tapped transformer will be discussed in this chapter. The primary purpose of the center-tapped transformer is to provide two equal voltages to the conventional full-wave rectifier.

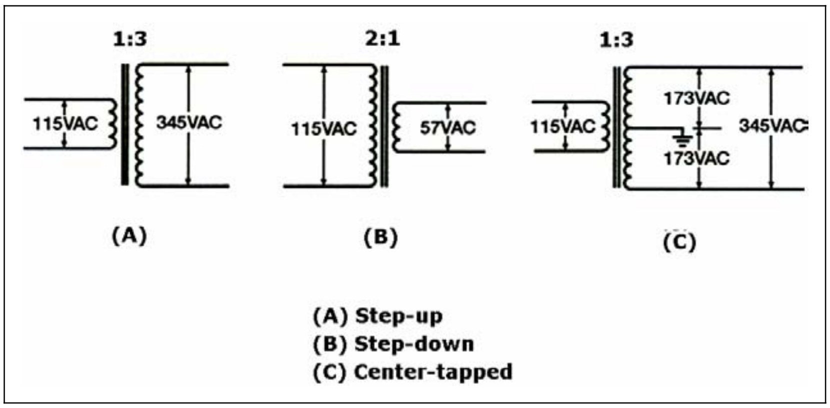


Figure 4-2. Common Types of Transformers

THE RECTIFIER

4-7. RECTIFICATION is the changing of an AC voltage to a pulsating DC voltage (see chapter 1). Let us look at how the process of RECTIFICATION occurs in a half-wave and a full-wave rectifier.

Half-Wave Rectifier

4-8. Since a silicon diode will pass current in only one direction, it is ideally suited for converting AC to DC. When AC voltage is applied to a diode, the diode conducts ONLY ON THE POSITIVE ALTERNATION OF VOLTAGE; that is, when the anode of the diode is positive in respect to the cathode. This simplest type of rectifier is the half-wave rectifier. Figure 4-3, view (A), shows that the half-wave rectifier uses only one diode. During the positive alternation of input voltage, the sine wave applied to the diode makes the anode positive with respect to the cathode. The diode then conducts, and current (I) flows from the negative supply lead (the secondary of the transformer), through the milliammeter, through the diode, and to the positive supply lead. As indicated by the shaded area of the output waveform in view (B), this current exists during the entire period

of time that the anode is positive in respect to the cathode (in other words, for the first 180 degrees of the input sine wave).

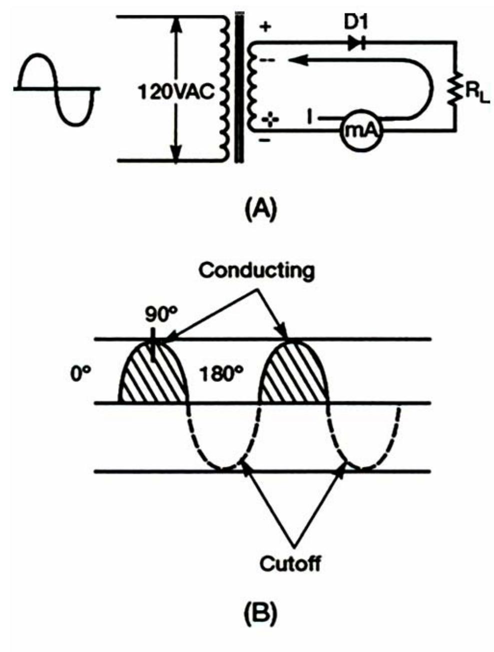


Figure 4-3. Simple Half-wave Rectifier

4-9. During the negative alternation of input voltage (dotted polarity signs), the anode is driven negative and the diode cannot conduct. When conditions such as these exist, the diode is in cutoff and remains in cutoff for 180 degrees. During this time, no current flows in the circuit. The circuit current therefore has the appearance of a series of positive pulses (see shaded areas on the waveform in Figure 4-3, view (B)). Notice that although the current is in the form of pulses, the current always flows in the same direction. Current that flows in pulses in the same direction is called PULSATING DC. The diode has thereby RECTIFIED the AC input voltage.

Root Mean Square, Peak, and Average Values

4-10. Figure 4-4, view (A) shows a comparison of the root mean square, peak, and average values of the types of waveforms associated with the half-wave rectifier. AC voltages are normally specified in terms of their RMS values. Therefore, when a 115-volt AC power source is mentioned in this chapter, it is specifying the RMS value of 115 volts AC. Use the following formula to compute peak values:

$$E_{rms} = E_{peak} \times .707$$

The peak value is always higher than the RMS value. To compute this, use the following formula:

$$E_{peak} = E_{rms} \times 1.414$$

Therefore, if the RMS value is 115 volts AC, then the peak value would be computed as follows:

$E_{peak} = E_{rms} \times 1.414$

$E_{peak} = 115 \text{ volts AC} \times 1.414$

$E_{peak} = 162.6 \text{ volts}$

4-11. The average value of a sine wave is 0 volts. Figure 4-4, view (B) shows how the average voltage changes when the negative portion of the sine wave is clipped off. Since the waveform swings positive but never negative (pass the "zero-volt" reference line), the average voltage is positive. The average voltage (E_{avg}) is determined by the equation:

Where: $E_{avg} = E_{peak} \times .318$

So: $E_{avg} = 162.6 \times .318$

$E_{avg} = 51.7 \text{ volts}$

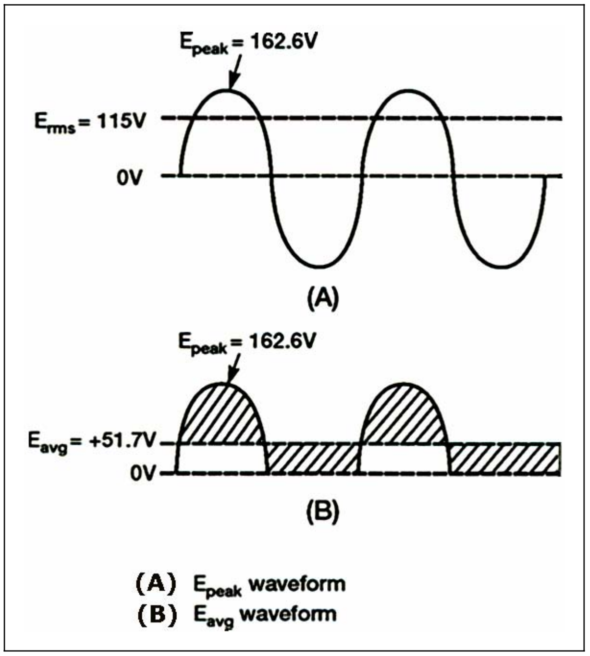


Figure 4-4. Comparison of E_{peak} to E_{avg} in a Half-wave Rectifier

Ripple Frequency

4-12. The half-wave rectifier gets its name from the fact that it conducts during only half the input cycle. Its output is a series of pulses with a frequency that is the same as the input frequency. So, when operated from a 60-Hz line, the frequency of the pulses is 60 Hz. This is called RIPPLE FREQUENCY.

Conventional Full-Wave Rectifier

4-13. A full-wave rectifier is a device that has two or more diodes arranged so that load current flows in the same direction during each half cycle of the AC supply. Figure 4-5 shows a diagram of a simple full-wave rectifier. The transformer supplies the source voltage for two diode rectifiers (D1 and D2). This power transformer has a center-tapped,

high-voltage secondary winding that is divided into two equal parts (W1 and W2). W1 provides the source voltage for D1 and W2 provides the source voltage for D2. The connections to the diodes are arranged so that the diodes conduct on alternate half cycles.

4-14. During one alternation of the secondary voltage, the polarities are as shown in Figure 4-5, view (A). The source for D2 is the voltage induced into the lower half of the secondary winding of the transformer (W2). At the specific instant of time shown in the figure, the anode voltage on D2 is negative and therefore cannot conduct. Throughout the period of time during which the anode of D2 is negative, the anode of Dl is positive. Since the anode of Dl is positive, it conducts, causing current to flow through the load resistor in the direction shown by the arrow.

4-15. Figure 4-5, view (B) shows the next half cycle of secondary voltage. Now the polarities across W1 and W2 are reversed. During this alternation, the anode of D1 is driven negative and Dl cannot conduct. For the period of time that the anode of Dl is negative, the anode of D2 is positive, permitting D2 to conduct. Notice that the anode current of D2 passes through the load resistor in the same direction, as did the current of Dl. In this circuit arrangement, a pulse of load current flows during each alternation of the input cycle. Since both alternations of the input voltage cycle are used, the circuit is called a FULL-WAVE RECTIFIER.

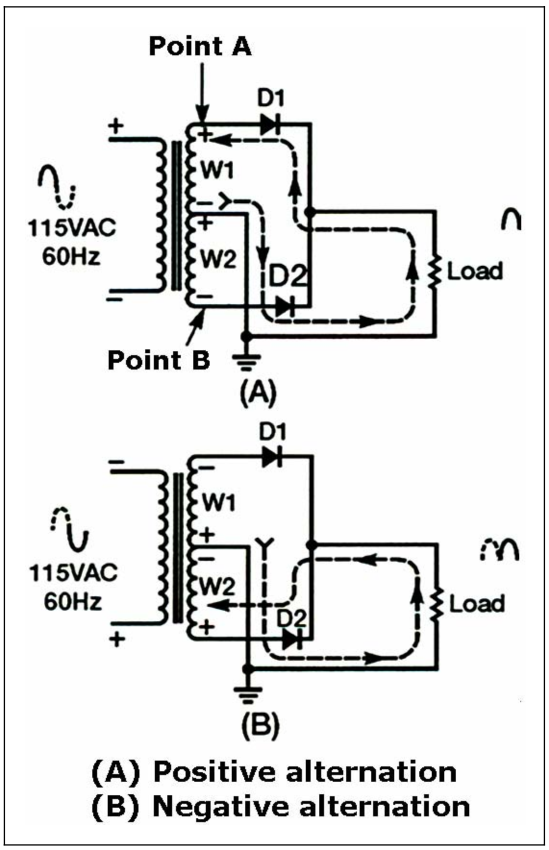


Figure 4-5. Simple Full-wave Rectifier

Practical Full-Wave Rectifier

4-16. Figure 4-6, view (A) shows a practical full-wave rectifier circuit. It uses two diodes (Dl and D2) and a center-tapped transformer (T1). When the center tap is grounded,

the voltages at the opposite ends of the secondary windings are 180 degrees out of phase with each other. So, when the voltage at point A is positive with respect to ground, the voltage at point B is negative with respect to ground. Let us examine the operation of the circuit during one complete cycle.

4-17. During the first half cycle (indicated by the solid arrows), the anode of Dl is positive with respect to ground and the anode of D2 is negative. Figure 4-6, view (A) shows that current flows from ground (center tap), up through the load resistor (R_L), through diode Dl to point A. In the transformer, current flows from point A, through the upper winding, and back to ground (center tap). When Dl conducts, it acts like a closed switch so that the positive half cycle is felt across the load (R_L).

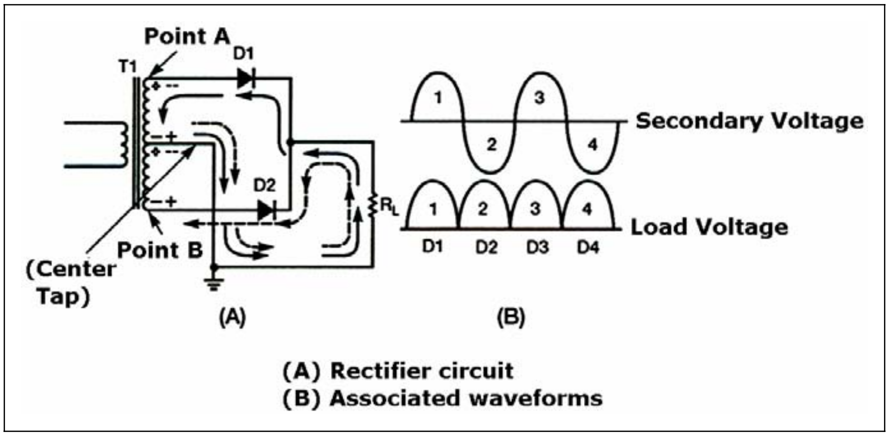


Figure 4-6. Practical Full-wave Rectifier

4-18. During the second half cycle (indicated by the dotted lines), the polarity of the applied voltage has reversed. Now the anode of D2 is positive with respect to ground and the anode of Dl is negative. Now only D2 can conduct. Current now flows, as shown, from ground (center tap), up through the load resistor (R_L), through diode D2 to point B of T1. In the transformer, current flows from point B up through the lower windings and back to ground (center tap). Notice that the current flows across the load resistor (R_L) in the SAME DIRECTION for both halves of the input cycle.

4-19. Figure 4-6, view (B) represents the output waveform from the full-wave rectifier. The waveform consists of two pulses of current (or voltage) for each cycle of input voltage. The ripple frequency at the output of the full-wave rectifier is therefore TWICE THE LINE FREQUENCY.

4-20. The higher frequency at the output of a full-wave rectifier offers a distinct advantage. Because of the higher ripple frequency, the output is closely approximate to pure DC. The higher frequency also makes filtering much easier than it is for the output of the half-wave rectifier.

4-21. In terms of peak value, the average value of current and voltage at the output of the full-wave rectifier is twice as great as that at the output of the half-wave rectifier. Figure 4-7 shows the relationship between the peak value and the average value. Since the output waveform is essentially a sine wave with both alternations at the same polarity, the average current or voltage is 63.7 percent (or 0.637) of the peak current or voltage. This is shown in the following equation:

Where:

E_{max} = the peak value of the load voltage pulse.

E_{avg} = 0.637 x E_{max} (the average load voltage).

I_{max} = the peak value of the load current pulse.

I_{avg} = 0.637 x I_{max} (the average load current).

Example: The total voltage across the high-voltage secondary of a transformer used to supply a full-wave rectifier is 300 volts. Find the average load voltage (ignore the drop across the diode).

Solution: Since the total secondary voltage (E_S) is 300 volts, each diode is supplied one-half of this value, or 150 volts. Since the secondary voltage is an RMS value, the formula for the peak load voltage is as follows:

$E_{max} = 1.414 \times E_s$

$E_{max} = 1.414 \times 150$

$E_{max} = 212$ volts

The average load voltage is computed as follows:

$E_{avg} = 0.637 \times E_{max}$

$E_{avg} = 0.637 \times 212$

$E_{avg} = 135$ volts

NOTE*:* If you have problems with this equation, review the portion of TC 9-60 that pertains to this subject.

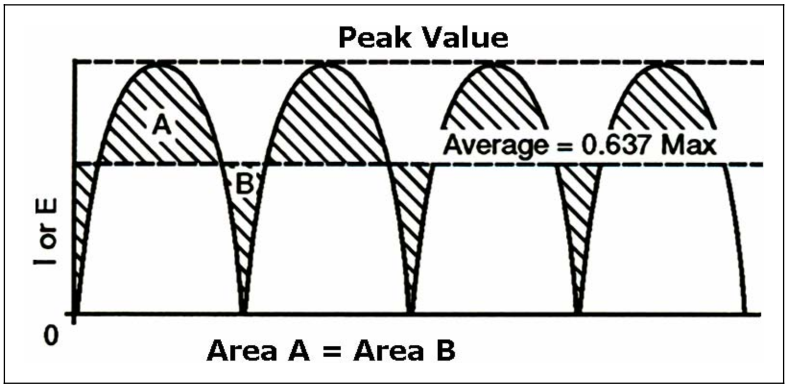


Figure 4-7. Peak and Average Values for a Full-wave Rectifier

4-22. Remember, every circuit has advantages and disadvantages. The full-wave rectifier is no exception. In studying about the full-wave rectifier, you may have found that by doubling the output frequency, the average voltage has doubled, and the resulting signal is much easier to filter because of the high ripple frequency. The only disadvantage is that the peak voltage in the full-wave rectifier is only half the peak voltage in the half-wave

rectifier. This is because the secondary of the power transformer in the full-wave rectifier is center tapped; therefore, only half the source voltage goes to each diode.

Bridge Rectifier

4-23. There is also a rectifier that produces the same peak voltage as a half-wave rectifier and the same ripple frequency as a full-wave rectifier. When four diodes are connected as shown in Figure 4-8, the circuit is called a BRIDGE RECTIFIER. The input to the circuit is applied to the diagonally opposite corners of the network and the output is taken from the remaining two corners.

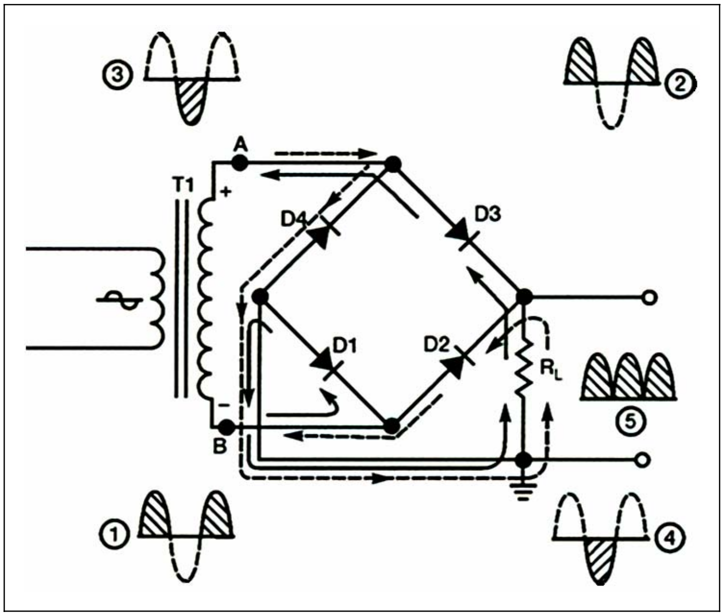


Figure 4-8. Bridge Rectifier

4-24. One complete cycle of operation will be discussed to help you understand how this circuit works. We will use a transformer that is working properly and where there is a positive potential at point A and a negative potential at point B. The positive potential at point A will forward bias D3 and reverse bias D4. The negative potential at point B will forward bias Dl and reverse bias D2. At this time D3 and D1 are forward biased and will allow current flow to pass through them (D4 and D2 are reverse biased and will block current flow). The path for current flow is from point B through Dl, up through R_L, through D3, through the secondary of the transformer back to point B. The solid arrows indicate this path. Waveforms (1) and (2) can be observed across Dl and D3.

4-25. One-half cycle later; the polarity across the secondary of the transformer reverses, forward biasing D2 and D4 and reverse biasing D1 and D3. Current flow will now be from point A through D4, up through R_L, through D2, up through the secondary of T1, and back to point A. The broken arrows indicate this path. Waveforms (3) and (4) can be observed across D2 and D4. You should have noted that the current flow through R_L is always in the same direction. In flowing through R_L this current develops a voltage corresponding to that shown in waveform (5). Since current flows through the load (R_L) during both half cycles of the applied voltage, this bridge rectifier is a full-wave rectifier.

4-26. One advantage of a bridge rectifier over a conventional full-wave rectifier is that with a given transformer, the bridge rectifier produces a voltage output that is nearly twice

as that of the conventional full-wave circuit. This may be shown by assigning values to some of the components (see Figure 4-9, views (A) and (B)). Assume that the same transformer is issued in both circuits. The peak voltage developed between points X and Y is 1,000 volts in both circuits. In the conventional full-wave circuit shown in view (A), the peak voltage from the center tap to either X or Y is 500 volts. Since only one diode can conduct at any instant, the maximum voltage that can be rectified at any instant is 500 volts. Therefore, the maximum voltage that appears across the load resistor is nearly (but never exceeds) 500 volts. This is a result of the small voltage drop across the diode. In the bridge rectifier shown in view (B), the maximum voltage that can be rectified is the full secondary voltage, which is 1,000 volts. Therefore, the peak output voltage across the load resistor is nearly 1,000 volts. With both circuits using the same transformer, the bridge rectifier circuit produces a higher output voltage than the conventional full-wave rectifier circuit.

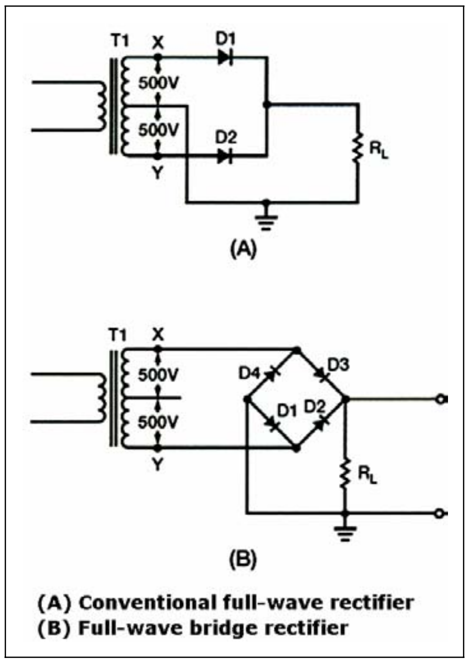


Figure 4-9. Comparison of a Conventional and Bridge Full-wave Rectifier

FILTERS

4-27. While the output of a rectifier is a pulsating DC, most electronic circuits require a substantially pure DC for proper operation. Single or multisection filter circuits, placed between the output of the rectifier and the load, provide this type of output. The following are the four basic types of filter circuits:

- Simple capacitor filter.
- LC choke-input filter.
- LC capacitor-input filter (pi-type).
- RC capacitor-input filter (pi-type).

4-28. Filtering is accomplished by the use of capacitors, inductors, and/or resistors in different combinations. Inductors are used as series impedances to oppose the flow of alternating (pulsating DC) current. Capacitors are used as shunt elements to bypass the

alternating components of the signal around the load (to ground). Resistors are used in place of inductors in low current applications.

4-29. Reviewing the properties of a capacitor we will see that a capacitor opposes any change in voltage. The opposition to a change in voltage is called capacitive reactance (X_C) and is measured in ohms. The capacitive reactance is determined by the frequency (f) of the applied voltage and the capacitance (C) of the capacitor. Use the following formula to make this determination:

$$X_C = \frac{1}{2\pi fC} \text{ or } \frac{.159}{fC}$$

4-30. You can see from the formula that if frequency or capacitance is increased, the X_C decreases. Since filter capacitors are placed in parallel with the load, a low X_C will provide better filtering than a high X_C. To do this, a better shunting effect of the AC around the load is provided (see Figure 4-10).

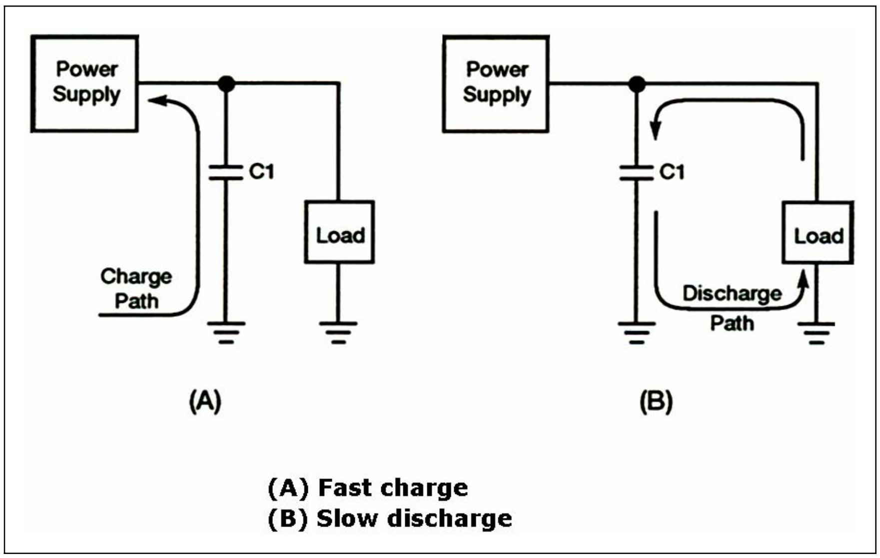


Figure 4-10. Capacitor Filter

4-31. To obtain a steady DC output, the capacitor must charge almost instantaneously to the value of applied voltage. Once charged, the capacitor must retain the charge as long as possible. The capacitor must have a short charge time constant. You can do this by keeping the internal resistance of the power supply as small as possible (fast charge time) and the resistance of the load as large as possible (slow discharge time). Figure 4-10, view (A), shows the fast charge time and view (B) shows the slow discharge time.

4-32. Remember learning from basic electricity that a one time constant is defined as the time it takes a capacitor to charge to 63.2 percent of the applied voltage or to discharge to 36.8 percent of its total charge. This action can be expressed by the following equation:

$$t = RC$$

Where:

R represents the resistance of the charge or discharge path.

C represents the capacitance of the capacitor.

A capacitor is considered fully charged after five RC time constants (see Figure 4-11). You can see that a steady DC output voltage is obtained when the capacitor charges rapidly and discharges as slowly as possible.

4-33. In filter circuits the capacitor is the common element to both the charge and the discharge paths. Therefore, to obtain the longest possible discharge time, you want the capacitor to be as large as possible. Another way to look at it is that the capacitor acts as a short circuit around the load (as far as the AC component is concerned) and since the larger the value of the capacitor (C), the smaller the opposition (X_C) or resistance to AC (see the following formula).

$$X_C = \frac{1}{2 \pi f C}$$

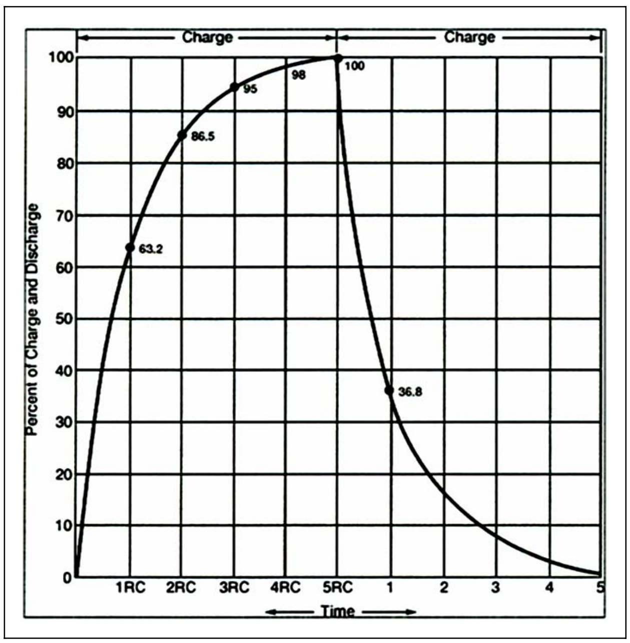


Figure 4-11. RC Time Constant

4-34. Let us look at inductors and their application in filter circuits. Remember, AN INDUCTOR OPPOSES ANY CHANGE IN CURRENT. A change in current through an inductor produces a changing electromagnetic field. The changing field, in turn, cuts the windings of the wire in the inductor and thereby produces a counterelectromotive force. It is the cemf that opposes the change in circuit current. Opposition to a change in current at a given frequency is called inductive reactance (X_L) and is measured in ohms. The X_L of an inductor is determined by the applied frequency and the inductance of the inductor (see the following formula).

$$X_L = 2 \pi f C$$

If frequency or inductance is increased, the X_L increases. Since inductors are placed in series with the load (see Figure 4-12), the larger the X_L, the larger the AC voltage developed across the load.

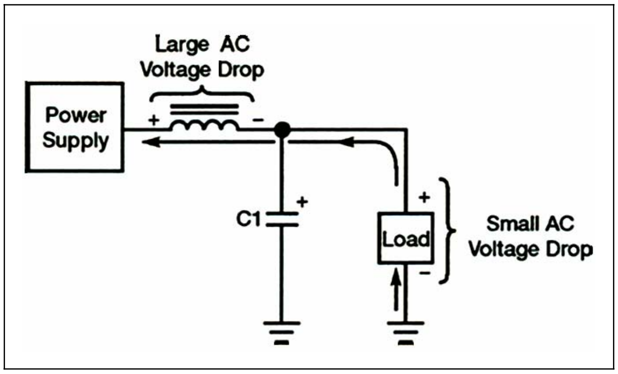


Figure 4-12. Voltage Drops in an Inductive Filter

4-35. When the current starts to flow through the coil, an expanding magnetic field builds up around the inductor. This magnetic field around the coil develops the cemf that opposes the change in current (see Figure 4-13).

4-36. When the rectifier current decreases (see Figure 4-14), the magnetic field collapses and again cuts the turns (windings) of wire, thereby inducing current into the coil. This additional current merges with the rectifier current and attempts to keep it at its original level.

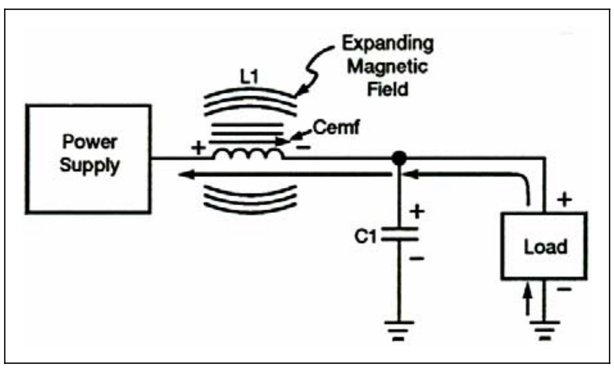


Figure 4-13. Inductive Filter (Expanding Field)

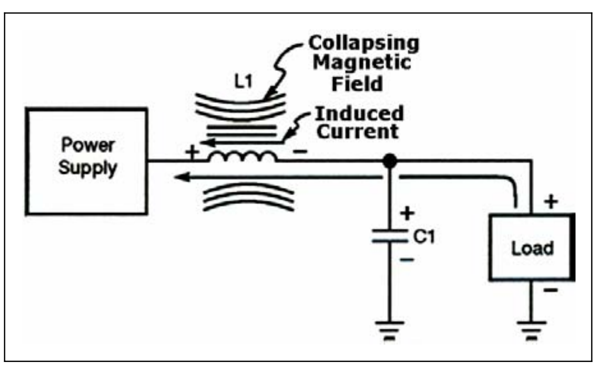


Figure 4-14. Inductive Filter (Collapsing Field)

4-37. There are many different types of filter circuits in use today. We will look some of the more common ones.

Capacitor Filter

4-38. The simple capacitor filter is the most basic type of power supply filter. The application of the simple capacitor filter is very limited. It is sometimes used on extremely high-voltage, low-current power supplies for cathode-ray and similar electron tubes that require very little load current from the supply. The capacitor filter is also used where the power-supply ripple frequency is not critical; this frequency can be relatively high. The capacitor (C1) (see Figure 4-15) is a simple filter connected across the output of the rectifier in parallel with the load.

4-39. When this filter is used, the RC charge time of the filter capacitor (C1) must be short and the RC discharge time must be long to eliminate ripple action. In other words, the capacitor must charge up fast, preferably with no discharge at all. Better filtering also results when the input frequency is high. Therefore, the full-wave rectifier output is easier to filter than that of the half-wave rectifier because of its higher frequency.

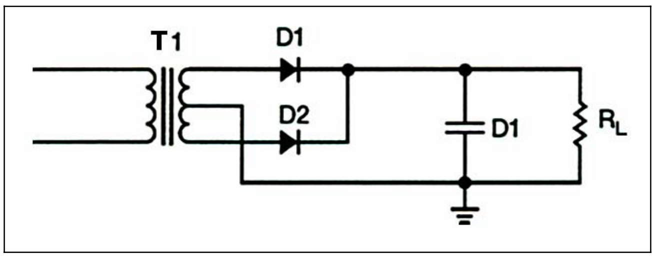


Figure 4-15. Full-wave Rectifier With a Capacitor Filter

4-40. To help understand the effect that filtering has on E_{avg}, a comparison of a rectifier circuit with a filter and one without a filter is shown in Figure 4-16, views (A) and (B). The output waveforms in Figure 4-16 represent the unfiltered and filtered outputs of the half-wave rectifier circuit. Current pulses flow through the load resistance (R_L) each time a diode conducts. The dashed line indicates the average value of output voltage. For the half-wave rectifier, E_{avg} is less than half (or approximately 0.318) of the peak output voltage. This value is still much less than that of the applied voltage. With no capacitor connected across the output of the rectifier circuit, the waveform in view (A) has a large pulsating component (ripple) compared with the average or DC component. When a capacitor is connected across the output (view B), the average value of output voltage (E_{avg}) is increased due to the filtering action of capacitor C1. A comparison of the waveforms (see Figure 4-16) shows that the addition of C1 to the circuit results in an increase in the average of the output voltage (E_{avg}) and a reduction in the amplitude of the ripple component (E_r), which is normally present across the load resistance.

4-41. The value of the capacitor is fairly large (several microfarads), so it presents a relatively low reactance to the pulsating current and it stores a substantial charge. The rate of charge for the capacitor is limited only by the resistance of the conducting diode that is relatively low. Therefore, the RC charge time of the circuit is relatively short. As a result, when the pulsating voltage is first applied to the circuit, the capacitor charges rapidly and almost reaches the peak value of the rectified voltage within the first few cycles. The capacitor attempts to charge to the peak value of the rectified voltage anytime a diode is conducting and tends to retain its charge when the rectifier output falls to zero (the

capacitor cannot discharge immediately). The capacitor slowly discharges through the load resistance (R_L) during the time the rectifier is nonconducting.

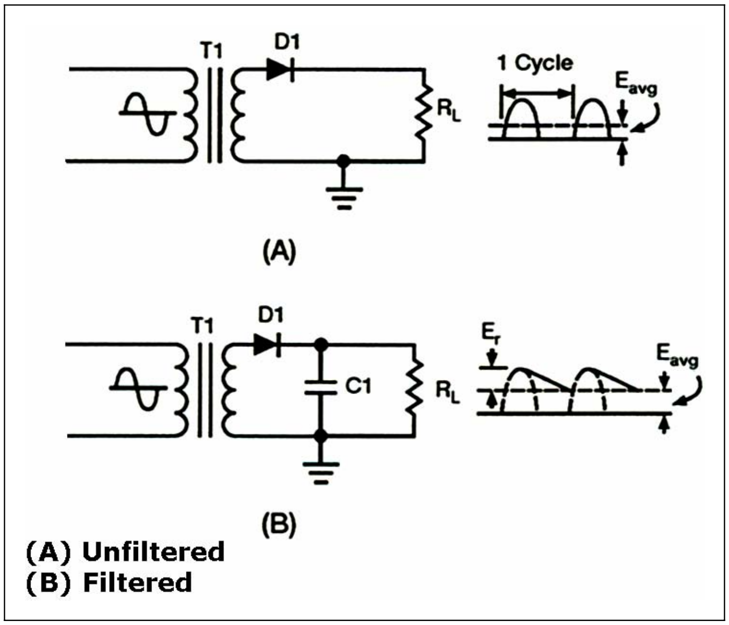


Figure 4-16. Half-wave Rectifier With and Without Filtering

4-42. The rate of discharge of the capacitor is determined by the value of capacitance and the value of the 1oad resistance. If the capacitance and load-resistance values are large, the RC charge time for the circuit is relatively long.

4-43. Let us consider a complete cycle of operation using a half-wave rectifier, a capacitive filter (C1), and a load resistor (R_L). The capacitive filter (C1), shown in Figure 4-17, view (A), is assumed to be large enough to ensure a small reactance to the pulsating rectified current. The resistance of R_L is assumed to be much greater than the reactance of C1 at the input frequency. When the circuit is energized, the diode conducts on the positive half cycle and current flows through the circuit, allowing C1 to charge. C1 will charge to approximately the peak value of the input voltage (the charge is less than the peak value because of the voltage drop across the diode (D1)). Figure 4-17, view (A) shows that the heavy solid line on the waveform indicates that the charge is C1. View (B) shows that the diode cannot conduct on the negative half cycle because the anode of Dl is negative in respect to the cathode. During this interval, C1 discharges through the load resistor (R_L). The discharge of C1 produces the downward slope as indicated by the solid line on the waveform in view (B). In contrast to the abrupt fall of the applied AC voltage from peak value to zero, the voltage across C1 (and thereby across R_L) during the discharge period gradually decreases until the time of the next half cycle of rectifier operation. Remember that for good filtering, the filter capacitor should charge up as fast as possible and discharge as little as possible.

4-44. Since practical values of C1 and R_L ensure a more or less gradual decrease of the discharge voltage, a substantial charge remains on the capacitor at the time of the next half cycle of operation. As a result, no current can flow through the diode until the rising AC input voltage at the anode of the diode exceeds the voltage of the charge remaining on C1. The charge on C1 is the cathode potential of the diode. When the potential on the anode

exceeds the potential on the cathode (the charge on C1), the diode again conducts and C1 begins to charge to approximately the peak value of the applied voltage.

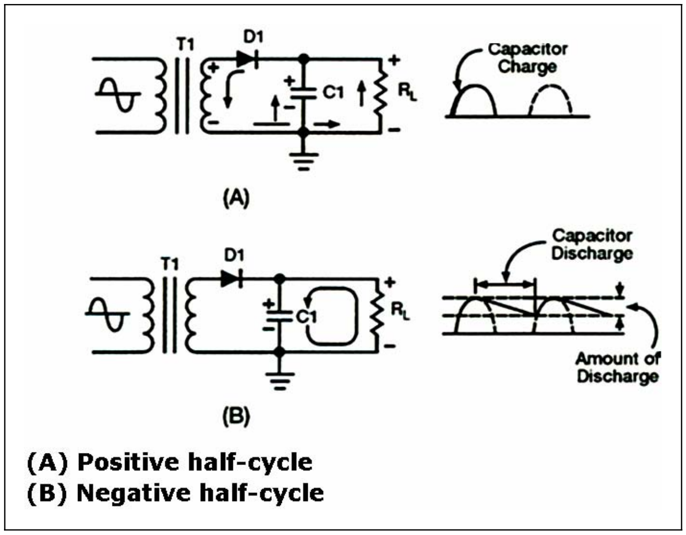


Figure 4-17. Capacitor Filter Circuit (Positive and Negative Half Cycles)

4-45. After the capacitor has charged to its peak value, the diode will cut off and the capacitor will start to discharge. Since the decrease of the AC input voltage on the anode is considerably more rapid than the decrease on the capacitor voltage, the cathode quickly becomes more positive than the anode, and the diode ceases to conduct.

4-46. Operation of the simple capacitor filter using a full-wave rectifier is basically the same as that discussed for the half-wave rectifier. Figure 4-18 shows that because one of the diodes is always conducting on either one of the alternations, the filter capacitor charges and discharges during each half cycle. Notice that each diode conducts only for that portion of time when the peak secondary voltage is greater than the charge across the capacitor.

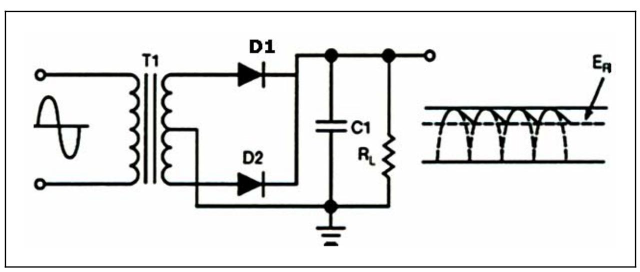


Figure 4-18. Full-wave Rectifier (With Capacitor Filter)

4-47. Remember that the ripple component (E_R) of the output voltage is an AC voltage and the average output voltage (E_{avg}) is the DC component of the output. Since the filter capacitor offers relatively low impedance to AC, the majority of the AC component flows through the filter capacitor. The AC component is therefore bypassed (shunted) around the load resistance and the entire DC component (or E_{avg}) flows through the load resistance. This statement can be clarified by using the below formula for X_C in a half-wave and full-wave rectifier.

$$X_C = \frac{1}{2\pi f C}$$

4-48. Next, you must establish some values for the circuit. As you can see from the calculations in Table 4-1, by doubling the frequency of the rectifier, you reduce the impedance of the capacitor by one-half. This allows the AC component to pass through the capacitor more easily. As a result, a full-wave rectifier output is much easier to filter than that of a half-wave rectifier. Remember, the smaller the X_C of the filter capacitor, in respect to the load resistance, the better the filtering action. If load resistance is made small, the load current increases, and the average value of output voltage (E_{avg}) decreases. The RC discharge time constant is a direct function of the value of the load resistance. Therefore, the rate of capacitor voltage discharge is a direct function of the current through the load. The greater the load current, the more rapid the discharge of the capacitor, and the lower the average value of output voltage. For this reason, the simple, capacitive filter is seldom used with rectifier circuits that must supply a relatively large load current. Using the simple capacitive filter in conjunction with a full-wave or bridge rectifier provides improved filtering because the increased ripple frequency decreases the capacitive reactance of the filter capacitor.

Table 4-1. Calculating Half-wave Rectifier and Full-wave Rectifier

HALF-WAVE RECTIFIER	FULL-WAVE RECTIFIER
FREQUENCY AT RECTIFIER OUTPUT: 60 Hz	FREQUENCY AT RECTIFIER OUTPUT: 120 Hz
VALUE OF FILTER CAPACITOR: 30μF	VALUE OF FILTER CAPACITOR: 30μF
LOAD RESISTANCE (R_L): 10κΩ	LOAD RESISTANCE (R_L): 10κΩ
$X_C = \frac{1}{2\pi fC}$	$X_C = \frac{1}{2\pi fC}$
$X_C = \frac{.159}{fC}$	$X_C = \frac{.159}{fC}$
$X_C = \frac{.159}{60 \times .000030}$	$X_C = \frac{.159}{120 \times .000030}$
$X_C = \frac{.159}{.0018}$	$X_C = \frac{.159}{.036}$
$X_C = 88.3\Omega$	$X_C = 44.16\Omega$

LC Choke-Input Filter

4-49. The LC choke-input filter is used primarily in power supplies where voltage regulation is important. It is also used where the output current is relatively high and subject to varying load conditions. This filter is used in high power applications such as those found in radars and communication transmitters.

4-50. Figure 4-19 shows that this filter consists of an input inductor (L1), or filter choke, and an output filter capacitor (C1). Inductor L1 is placed at the input to the filter and is in series with the output of the rectifier circuit. Since the action of an inductor is to oppose any change in current flow, the inductor tends to keep a constant current flowing to the load throughout the complete cycle of the applied voltage. As a result, the output voltage never reaches the peak value of the applied voltage. Instead, the output voltage approximates the average value of the rectified input to the filter (see Figure 4-19). The reactance of the inductor (X_L) reduces the amplitude of ripple voltage without reducing the DC output voltage by an appreciable amount (the DC resistance of the inductor is just a few ohms).

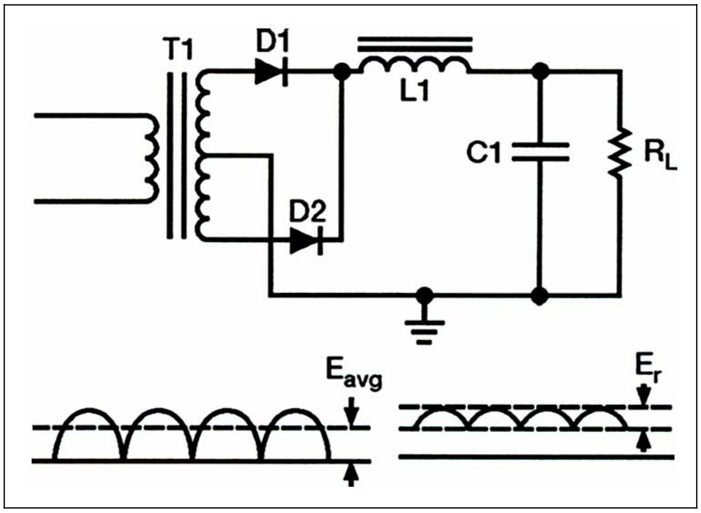


Figure 4-19. LC Choke-input Filter

4-51. The shunt capacitor (C1) charges and discharges at the ripple frequency rate. However, the amplitude of the ripple voltage (E_r) is relatively small because the inductor (L1) tends to keep a constant current flowing from the rectifier circuit to the load. The reactance of the shunt capacitor (X_C) also presents low impedance to the ripple component existing at the output of the filter, and thereby shunts the ripple component around the load. The capacitor attempts to hold the output voltage relatively constant at the average value of the voltage.

4-52. The value of the filter capacitor (C1) must be relatively large to present a low opposition (X_C) to the pulsating current and to store a substantial charge. The rate of the charge for the capacitor is limited by the following:

- Low impedance of the AC source (the transformer).
- By the small resistance of the diode.
- By the cemf developed by the coil.

Therefore, the RC charge time constant is short compared to its discharge time. Figure 4-20, views (A) and (B) shows the comparison in RC charge and discharge paths. Consequently, when the pulsating voltage is first applied to the LC choke-input filter, the inductor (L1) produces a cemf that opposes the constantly increasing input voltage. The net result is to effectively prevent the rapid charging of the filter capacitor (C1). Instead of reaching the peak value of the input voltage, C1 only charges to the average value of the input voltage. After the input voltage reaches its peak and decreases sufficiently, the capacitor (C1) attempts to discharge through the load resistance (R_L). Figure 4-20, view (B) shows that C1 will only partially discharge because of its relatively long discharge time constant. The larger the value of the filter capacitor, the better the filtering action. However, because of physical size, there is a practical limitation to the maximum value of the capacitor.

4-53. The inductor (also referred to as the filter choke or coil) serves to maintain the current flow to the filter output (R_L) at a nearly constant level during the charge and discharge periods of the filter capacitor. The inductor (L1) and the capacitor (C1) form a voltage divider for the AC component (ripple) of the applied input voltage (see Figure 4-21, views (A) and (B)). As far as the ripple component is concerned, the inductor offers high impedance (Z) and the capacitor offers low impedance (view B). As a result, the ripple component (E_r) appearing across the load resistance is greatly attenuated (reduced). The inductance of the filter choke opposes changes in the value of the current flowing through it. Therefore, the average value of the voltage produced across the capacitor contains a much smaller value of ripple component (E_r) than the value of ripple produced across the choke.

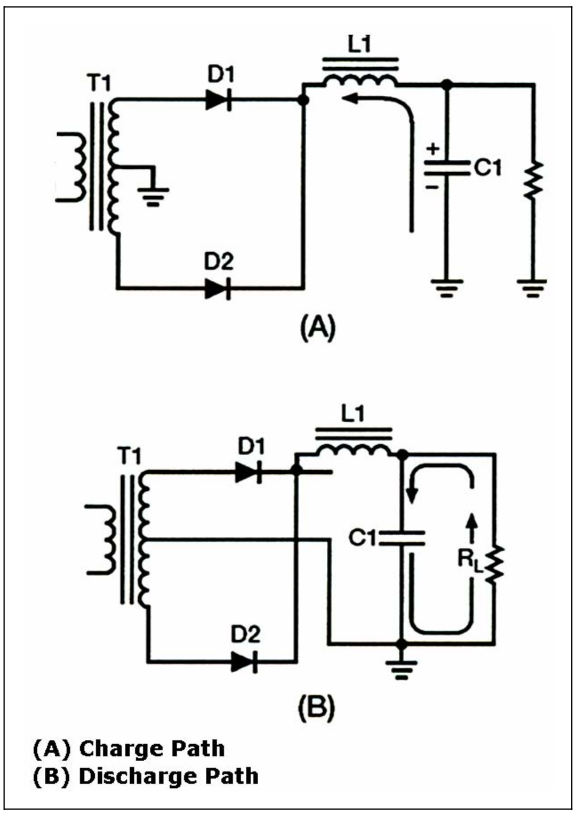
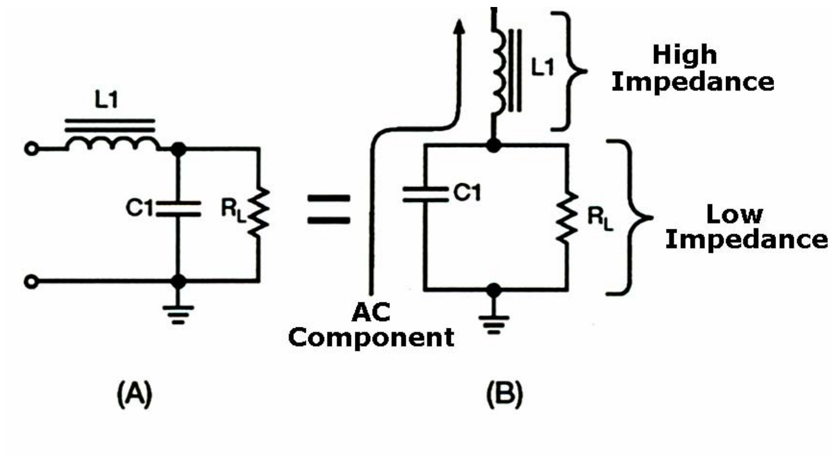


Figure 4-20. LC Choke-input Filter (Charge and Discharge Paths)



(A) LC Choke-Input Filter
(B) Equivalent Circuit

Figure 4-21. LC Choke-input Filter (Voltage Divider)

4-54. Figure 4-22 shows a complete cycle of operation for a full-wave rectifier circuit used to supply the input voltage to the filter. The rectifier voltage is developed across the capacitor (C1). The ripple voltage at the output of the filter is the alternating component of the input voltage reduced in amplitude by the filter section. Each time the anode of a diode goes positive with respect to the cathode, the diode conducts and C1 charges. Conduction occurs twice during each cycle for a full-wave rectifier. For a 60-Hz supply, this produces a 120-Hz ripple voltage. Although the diodes alternate (one conducts while the other is nonconducting), the filter input voltage is not steady. As the anode voltage of the conducting diode increases (on the positive half of the cycle), capacitor C1 charges (the charge being limited by the impedance of the secondary transformer winding, the diode's forward [cathode-to-anode] resistance, and the counter electromotive force developed by the choke). During the nonconducting interval (when the anode voltage drops below the capacitor charge voltage), C1 discharges through the load resistor (R_L). Since the components in the discharge path have a long time constant, C1 discharges more slowly than it charges.

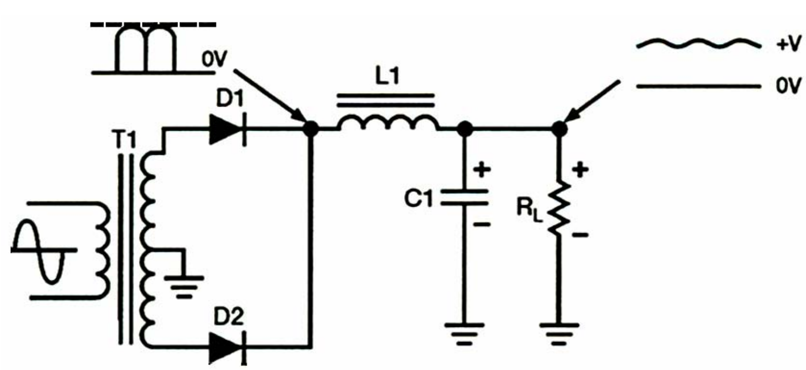


Figure 4-22. Filtering Action of the LC Choke-input Filter

4-55. The choke (L1) is usually a large value (from 1 to 20 henries) and offers a large inductive reactance to the 120-Hz ripple component produced by the rectifier. Therefore, the effect that L1 has on the charging of the capacitor (C1) must be considered. Since L1 is connected in series with the parallel branch consisting of C1 and R_L, a division of the ripple (AC) voltage and the output (DC) voltage occurs. The greater the impedance of the choke, the less the ripple voltage that appears across C1 and the output. The DC output voltage is fixed mainly by the DC resistance of the choke.

4-56. Now that you know how the LC choke-input filter functions, we will look at it with actual component values applied. For simplicity, the input frequency at the primary of the transformer will be 117 volts, 60 Hz. Half-wave and full-wave rectifier circuits will be used to provide the input to the filter.

4-57. Figure 4-23 shows the half-wave configuration. The basic parameters are as follows:

> With 117 volts AC rms applied to the T1 primary, 165 volts AC peak-to-peak is available at the secondary [(117 V) x (1.414) = 165 V]

Remember that the ripple frequency of this half-wave rectifier is 60 Hz. Therefore, using the below formula, the capacitive reactance of C1 is computed as follows:

$$X_C = \frac{1}{2\pi f C}$$

$$X_C = \frac{1}{(2)(3.14)(60)(10)(10^{-6})}$$

$$X_C = \frac{(1)(10^6)}{3768}$$

$$X_C = 265 \text{ ohms}$$

This means that the capacitor (C1) offers 265 ohms of opposition to the ripple current. However, the capacitor offers an infinite impedance to DC. Using the following formula, the inductive reactance of L1 is computed as follows:

$$X_L = 2\pi f L$$

$$X_L = (2)(3.14)(60)(10)$$

$$X_L = 3.8 \text{ kilohms}$$

4-58. The above calculation shows that L1 offers a relatively high opposition (3.8 kilohms) to the ripple in comparison to the opposition offered by C1 (265 ohms). Therefore, more ripple voltage will be dropped across L1 than across C1. The impedance of C1 (265 ohms) is also relatively low in respect to the resistance of the load (10 kilohms). Therefore, more ripple current flows through C1 than the load. In other words, C1 shunts most of the AC component around the load.

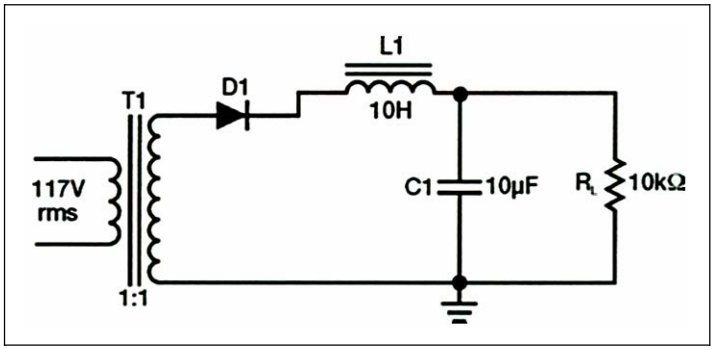


Figure 4-23. Half-wave Rectifier with an LC Choke-input Filter

4-59. Redraw the filter circuit so that you can see the voltage divider action (see Figure 4-24, view (A). Remember, the 165 volts peak-to-peak 60 Hz provided by the rectifier consists of both an AC and a DC component. In Figure 4-24, you can see that the capacitor (C1) offers the least opposition (265 ohms) to the AC component. Therefore, the greatest amount of AC will flow through C1 (the heavy line indicates the AC current flow through the capacitor). So, the capacitor bypasses, or shunts, most of the AC around the load.

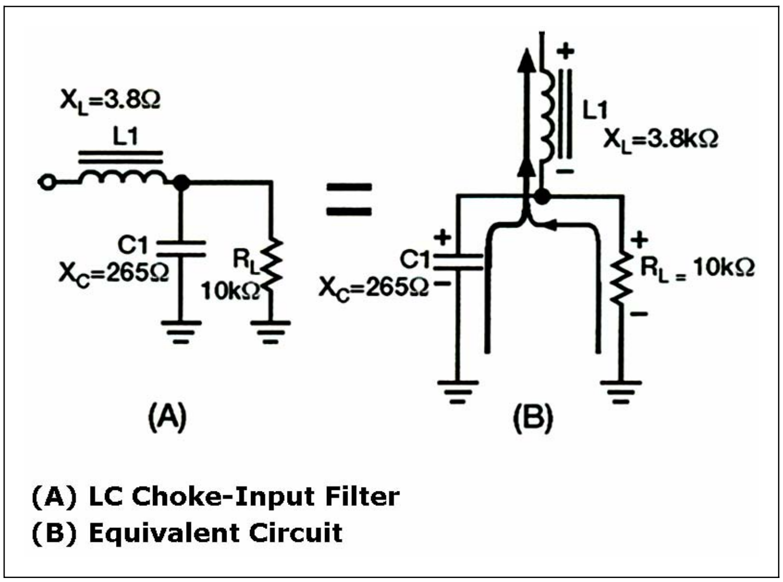


Figure 4-24. AC Component in an LC Choke-input Filter

4-60. By combining the X_C of C1 and the resistance of R_L into an equivalent circuit (see Figure 4-24, view (B)), you will have a total resistance of 258 ohms. To compute this, use the following formula:

$$RT = \frac{(R1)(R2)}{R1 + R2}$$

You now have a voltage divider (see Figure 4-25). Notice that because of the impedance ratios, a large amount of ripple voltage is dropped across L1 and a substantially smaller amount is dropped across C1 and R_L. You can further increase the ripple voltage across L1 by increasing the inductance ($X_L = 2 \pi f L$).

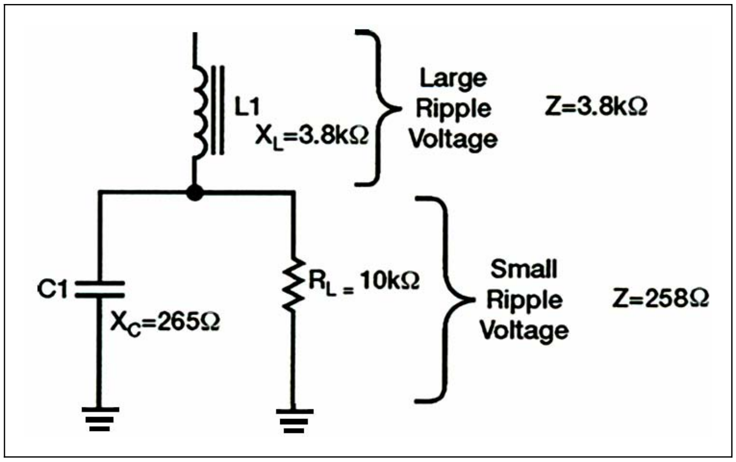


Figure 4-25. Equivalent Circuit of an LC Choke-input Filter

4-61. We will now look at the DC component of the applied voltage. Remember, a capacitor offers an infinite (∞) impedance to the flow of DC. Therefore, the DC component must flow through R_L and L1. As far as the DC is concerned, the capacitor does not exist. The coil and the load are therefore in series with each other. The DC resistance of a filter choke is very low (50 ohms average). Consequently, most of the DC component is developed across the load and a very small amount of the DC voltage is dropped across the coil (see Figure 4-26).

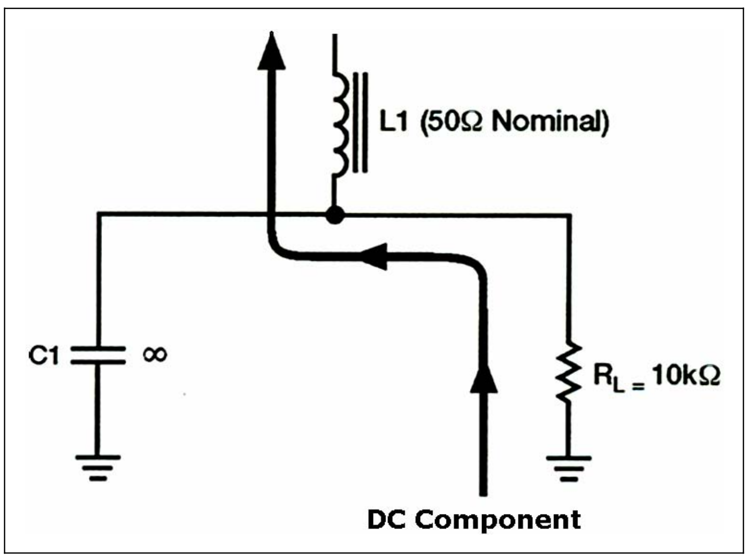


Figure 4-26. DC Component in an LC Choke-input Filter

4-62. Notice that both the AC and DC components flow through Ll. Since it is frequency sensitive, the coil provides a large resistance to AC and a small resistance to DC. In other words, the coil opposes any change in current. This property makes the coil a highly desirable filter component. Notice that the filtering action of the LC choke-input filter is improved when the filter is used in conjunction with a full-wave rectifier (see Figure 4-27). This is due to the decrease in the X_C of the filter capacitor and the increase in the X_L of the choke. Remember, ripple frequency of a full-wave rectifier is twice that of a

half-wave rectifier. For a 60-Hz input, the ripple will be 120 Hz. The X_C of C1 and the X_L of L1 is calculated as follows:

$$X_C = \frac{1}{2\,\pi\,f\,C}$$

$$X_C = \frac{1}{(2)(3.14)(60)(10)10^{-6})}$$

$$X_C = \frac{(1)(10^6)}{7536}$$

$$X_C = 132.5\,\text{ohms}$$

$$X_L = 2\pi f\,L$$

$$X_L = (2)(3.14)(120)(10)$$

$$X_L = 7.5\,\text{kilohms}$$

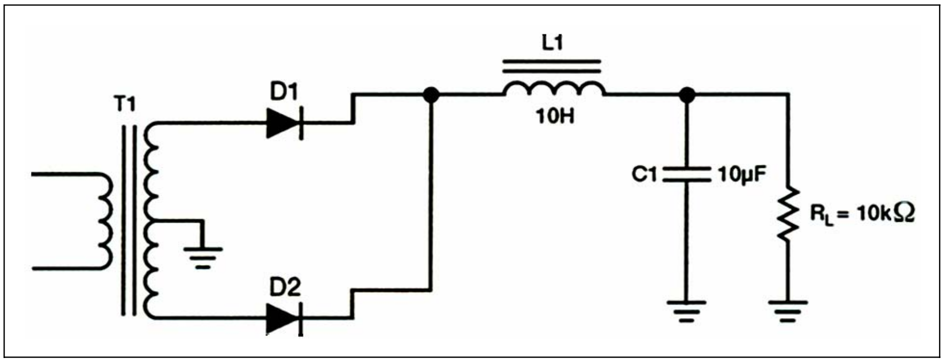


Figure 4-27. Full-wave Rectifier With an LC Choke-input Filter

4-63. When the X_C of a filter capacitor is decreased, it provides less opposition to the flow of AC. The greater the AC flow through the capacitor, the lower the flow through the load. Conversely, the larger the X_L of the choke, the greater the amount of AC ripple developed across the choke. Consequently, less ripple is developed across the load and better filtering is obtained.

4-64. The filter capacitors are subject to open circuits, short circuits, and excessive leakage. The series inductor is subject to open windings and occasionally, shorted turns or a short circuit to the core.

4-65. The filter capacitor in the LC choke-input filter circuit is not subject to extreme voltage surges because of the protection offered by the inductor. However, the capacitor can become open, leaky, or shorted.

4-66. Shorted turns in the choke may reduce the value of inductance below the critical value. This will result in excessive peak-rectifier current, accompanied by an abnormally high output voltage, excessive ripple amplitude, and poor voltage regulation.

4-67. A choke winding that is open or a choke winding which is shorted to the core will result in a no-output condition. A choke winding, which is shorted to the core, may cause overheating of the rectifier element(s) and blown fuses.

4-68. With the supply voltage removed from the input to the filter circuit, one terminal of the capacitor can be disconnected from the circuit. Check the capacitor with a capacitance analyzer to determine its capacitance and leakage resistance. You must use the correct polarity at all times when the capacitor is electrolytic. A decrease in capacitance or losses within the capacitor can decrease the efficiency of the filter and can produce excessive ripple amplitude.

Resistor-Capacitor Filters

4-69. The RC capacitor-input filter is limited to applications in which the load current is small. This type of filter is used in power supplies where the load current is constant and voltage regulation is not necessary. For example, RC filters are used in high-voltage power supplies for CRTs and in decoupling networks for multistage amplifiers.

4-70. Figure 4-28 shows an RC capacitor-input filter and associated waveforms. Half-wave and full-wave rectifiers are used to provide the inputs. The waveforms shown in view (A) represent the unfiltered output from a typical rectifier circuit. Notice that the dashed lines in view (A) indicate the average value of output voltage (E_{avg}) for the half-wave rectifier. The average output voltage (E_{avg}) is less than half (approximately 0.318) the amplitude of the voltage peaks. The average value of output voltage (E_{avg}) for the full-wave rectifier is greater than half (approximately 0.637), but is still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component (ripple) as compared to the average (or DC) component.

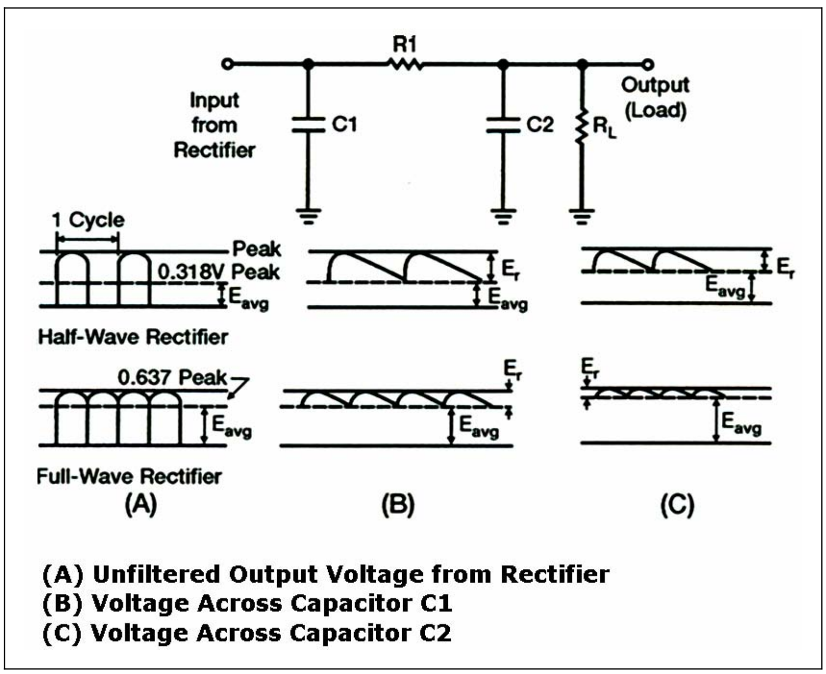


Figure 4-28. RC Filter and Waveforms

4-71. The RC filter in Figure 4-28 consists of an input filter capacitor (C1), a series resistor (R1), and an output filter capacitor (C2). This filter is sometimes referred to as an RC pi-section filter because its schematic symbol resembles the Greek letter π.

4-72. The single capacitor filter is suitable for many noncritical, low-current applications. However, when the load resistance is very low or when the percent of ripple must be held to an absolute minimum, the capacitor value required must be extremely large. While electrolytic capacitors are available in sizes up to 10,000 microfarads or greater, the large sizes are quite expensive. A more practical approach is to use a more sophisticated filter that can do the same job but that has lower capacitor values (such as the RC filter).

4-73. Figure 4-28, views (A), (B), and (C) shows the output waveforms of a half-wave and a full-wave rectifier. Each waveform is shown with an RC filter connected across the output. The following explanation of how a filter works will show you that an RC filter of this type does a much better job than the single capacitor filter.

4-74. C1 performs exactly the same function as it did in the single capacitor filter. It is used to reduce the percentage of ripple to a relatively low value. Therefore, the voltage across C1 might consist of an average DC value of +100 volts with a ripple voltage of 10 volts peak-to-peak. This voltage is passed on to the R1-C2 network, which reduces the ripple even further.

4-75. C2 offers an infinite impedance (resistance) to the DC component of the output voltage. Therefore, the DC voltage is passed to the load, but reduced in value by the amount of the voltage drop across R1. However, R1 is generally small compared to the load resistance. Therefore, the drop in the DC voltage by R1 is not a drawback.

4-76. Component values are designed so that the resistance of R1 is much greater than the reactance (X_C) of C2 at the ripple frequency. C2 offers very low impedance to the AC ripple frequency. Since the AC ripple senses a voltage divider consisting of R1 and C2 between the output of the rectifier and ground, most of the ripple voltage is dropped across R1. Only a trace of the ripple voltage can be seen across C2 and the load. In extreme cases where the ripple must be held to an absolute minimum, a second stage of RC filtering can be added. In practice, the second stage is rarely required. The RC filter is extremely popular because smaller capacitors can be used with good results.

4-77. The following are some disadvantages of the RC filter:

- The voltage drop across R1 takes voltage away from the load.
- Power is wasted in R1 and is dissipated in the form of unwanted heat.
- If the load resistance changes, the voltage across the load will change.

However, in many cases, the advantages of the RC filter outweigh the disadvantages.

4-78. The shunt capacitors (C1 and C2) are subject to an open circuit, a short circuit, or excessive leakage. The series filter resistor (R1) is subject to changes in value and occasionally opens. Any of these troubles can be easily detected.

4-79. The input capacitor (C1) has the greatest pulsating voltage applied to it and is the most susceptible to voltage surges. As a result, the input capacitor is frequently subject to voltage breakdown and shorting. The remaining shunt capacitor (C2) in the filter circuit is not subject to voltage surges because of the protection offered by the series filter resistor (R1). However, a shunt capacitor can become open, leaky, or shorted.

4-80. A shorted capacitor or an open filter resistor results in a no-output indication. An open filter resistor results in an abnormally high DC voltage at the input to the filter and no voltage at the output of the filter. Leaky capacitors or filter resistors that have lost their

effectiveness or filter resistors that have decreased in value, result in an excessive ripple amplitude in the output of the supply.

Inductance-Capacitor Capacitor-Input Filter

4-81. The LC capacitor-input filter is one of the most commonly used filters. This type of filter is used primarily in radio receivers, small audio amplifier power supplies, and in any type of power supply where the output current is low and the load current is relatively constant.

4-82. Figure 4-29 shows an LC capacitor-input filter and associated waveforms. Half-wave and full-wave rectifier circuits are used to provide the input. The waveforms shown in view (A) represent the unfiltered output from a typical rectifier circuit. Notice that the average value of output voltage (E_{avg}), indicated by the dashed lines, for the half-wave rectifier is less than half the amplitude of the voltage peaks. The average value of output voltage (E_{avg}) for the full-wave rectifier is greater than half, but is still less than the peak amplitude of the rectifier-output waveform with no filter connected across the output of the rectifier circuit (which results in unfiltered output voltage). The waveform has a large value of pulsating component (ripple) as compared to the average (or DC) component.

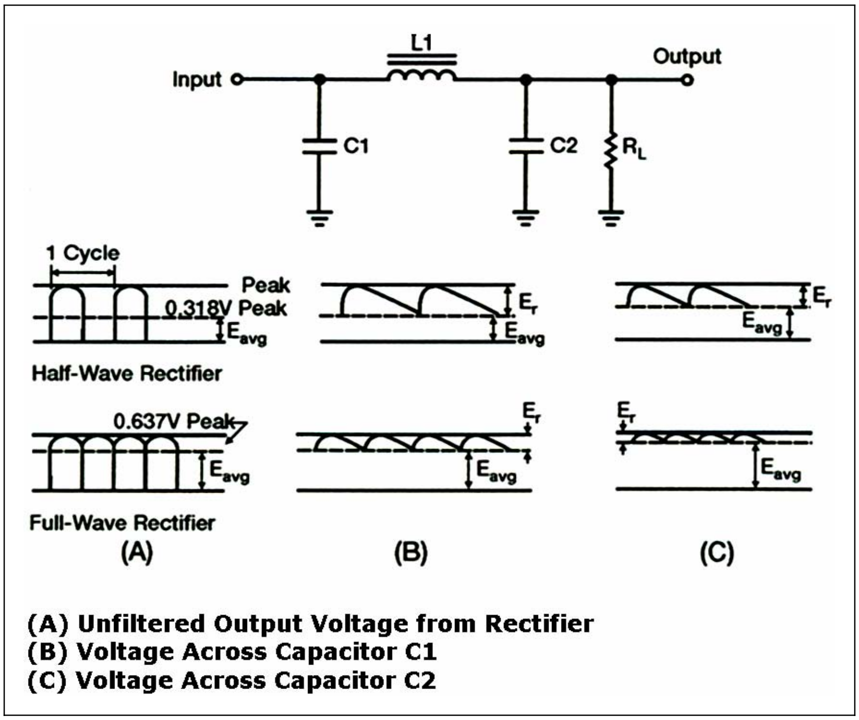


Figure 4-29. LC Filter and Waveforms

4-83. C1 reduces the ripple to a relatively low level (see Figure 4-29, view B). L1 and C2 form the LC filter that reduces the ripple even further. L1 is a large value iron-core inductor (choke). L1 has a high value of inductance and a high value of X_L that offers a high reactance to the ripple frequency. At the same time, C2 offers a very low reactance to AC ripple. L1 and C2 form an AC voltage divider and because the reactance of L1 is much higher than that of C2, most of the ripple voltage is dropped across L1. Only a slight trace of ripple appears across C2 and the load (see Figure 4-29, view C).

4-84. While the L1-C2 network greatly reduces AC ripple, it has little affect on DC. Remember that an inductor offers no reactance to DC. The only opposition to current flow is the resistance of the wire in the choke. Generally, this resistance is very low and the DC voltage drop across the coil is minimal. Therefore, the LC filter overcomes the disadvantages of the RC filter.

4-85. Aside from the voltage divider effect, the inductor improves filtering in another way. Remember that an inductor resists changes in the magnitude of the current flowing through it. Consequently, when the inductor is placed in series with the load, the inductor maintains steady current. In turn, this helps the voltage across the load remain constant when size of components is a factor.

4-86. The LC filter provides good filtering action over a wide range of currents. The capacitor filters best when the load is drawing little current. So, the capacitor discharges very slowly and the output voltage remains almost constant. However, the inductor filters best when the current is highest. The complementary nature of these two components ensures that good filtering will occur over a wide range of currents.

4-87. The two disadvantages of the LC filter are that it is more expensive than the RC filter (because an iron-core choke costs more than a resistor) and of its size. The iron-core choke is bulky and heavy, which usually makes the LC filter unsuitable for many applications.

4-88. Shunt capacitors are subject to open circuits, short circuits, and excessive leakage. Series inductors are subject to open windings and occasionally shorted turns or a short circuit to the core.

4-89. The input capacitor (C1) has the greatest pulsating voltage applied to it, is the most susceptible to voltage surges, and has a generally higher average voltage applied. As a result, the input capacitor is frequently subject to voltage breakdown and shorting. The output capacitor (C2) is not as susceptible to voltage surges because of the series protection offered by the series inductor (L1). However, the capacitor can become open, leaky, or shorted.

4-90. A shorted capacitor, an open filter choke, or a choke winding which is shorted to the core, results in a no-output indication. A shorted capacitor (depending on the magnitude of the short) may cause a shorted rectifier, transformer, or filter choke, which may result in a blown fuse in the primary of the transformer. An open filter choke results in an abnormally high DC voltage at the input to the filter and no voltage at the output of the filter. A leaky or open capacitor in the filter circuit results in a low DC output voltage. This condition is generally accompanied by excessive ripple amplitude. Shorted turns in the winding of a filter choke reduce the effective inductance of the choke and decrease its filtering efficiency. As a result, the ripple amplitude increases.

VOLTAGE REGULATION

4-91. Ideally, the output of most power supplies should be a constant voltage. Unfortunately, this is difficult to achieve. The following are the two factors that can cause the output voltage to change.

- The first factor is that the AC line voltage is not constant. The so-called 115 volts AC can vary from about 105 volts AC to 125 volts AC. This means that the peak AC voltage to which the rectifier responds can vary from about 148 volts to 177 volts. The AC line voltage alone can be responsible for nearly a 20 percent change in the DC output voltage.
- The second factor that can change the DC output voltage is a change in the load resistance. In complex electronic equipment, the load can change as circuits are switched in and out. In a television receiver, the load on a particular power supply may depend on the brightness of the screen, the control settings, or even the channel selected. These variations in load resistance tend to change the applied DC voltage because the power supply has a fixed internal resistance. If the load resistance decreases, the internal resistance of the power supply drops more voltage. This causes a decrease in the voltage across the load.

4-92. Many circuits are designed to operate with a particular supply voltage. When the supply voltage changes, the operation of the circuit may be adversely affected. Consequently, some types of equipment must have power supplies that produce the same output voltage regardless of changes in the load resistance or changes in the AC line voltage. This constant output voltage may be achieved by adding a circuit called the VOLTAGE REGULATOR at the output of the filter. There are so many different types of regulators in use today that it is impossible to discuss them all.

LOAD REGULATION

4-93. A commonly used FIGURE OF MERIT for a power supply is its PERCENT OF REGULATION. The figure of merit gives us an indication of how much the output voltage changes over a range of load resistance values. The percent of regulation aids in the determination of the type of load regulation needed. Percent of regulation is determined by the following equation:

$$\text{Percent of Regulation} = \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100$$

This equation compares the change in output voltage at the two loading extremes to the voltage produced at full loading. For example, assume that a power supply produces 12 volts when the load current is zero. If the output voltage drops to 10 volts when full load current flows, the percent of regulation is computed by using the following formula:

$$\begin{aligned}\text{Percent of Regulation} &= \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100 \\ &= \frac{12 - 10}{10} \times 100 \\ &= \frac{2}{10 \times 100} \\ &= 20\%\end{aligned}$$

4-94. Ideally, the output voltage should not change over the full range of operation. That is, a 12-volt power supply should produce 12 volts at no load, at full load, and at all points in between. In this case, the percent of regulation would be computed by using the following formula:

$$\text{Percent of Regulation} = \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100$$

$$= \frac{12 - 12}{12} \times 100$$

$$= \frac{0}{12} \times 100$$

$$= 0\ \%$$

Therefore, zero-percent load regulation is the ideal situation. It means that the output voltage is constant under all load conditions. While you should strive for zero-percent load regulation, in practical circuits you must settle for something less ideal. Even so, by using a voltage regulator, you can hold the percent of regulation to a very low value.

REGULATORS

4-95. You should know that the output of a power supply varies with changes in input voltage and circuit load current requirements. Since many electronic types of equipment require operating voltages and currents that must remain constant, some form of regulation is necessary. Circuits that maintain power supply voltages or current outputs within specified limits, or tolerances, are called REGULATORS. Depending on their specific application, they are designated as DC voltage or DC current regulators.

4-96. Voltage regulator circuits are additions to basic power supply circuits that are made up of rectifier and filter sections (see Figure 4-30). The purpose of the voltage regulator is to provide an output voltage with little or no variation. Regulator circuits sense changes in output voltages and compensate for the changes. Regulators that maintain voltages within plus or minus (±)0.1 percent are quite common.

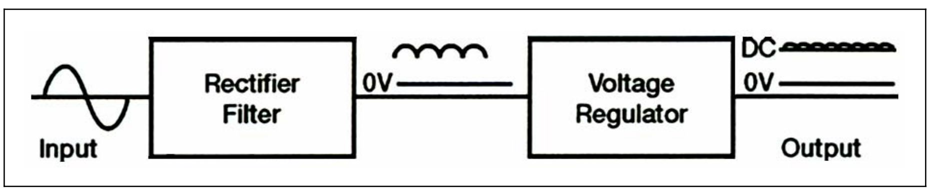


Figure 4-30. Block Diagram of a Power Supply and Regulator

Series and Shunt Voltage Regulators

4-97. The two basic types of voltage regulators are classified as either SERIES or SHUNT. The type depends on the location or position of the regulating element(s) in relation to the circuit load resistance. Figure 4-31 shows these two basic types of voltage regulators. In actual practice, the circuitry of regulating devices may be quite complex. Broken lines have been used in the figure to highlight the differences between the series and shunt regulators.

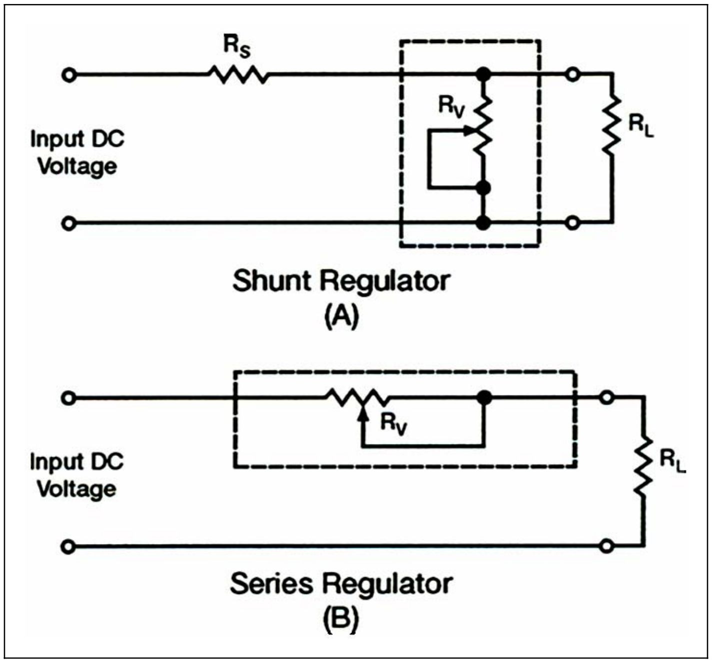


Figure 4-31. Simple Series and Shunt Voltage Regulators

4-98. The schematic drawing in Figure 4-31, view (A) is that of a shunt-type regulator. It is called a shunt-type regulator because the regulating device is connected in parallel with the load resistance. The schematic drawing in view (B) is that of a series regulator. It is called a series regulator because the regulating device is connected in series with the load resistance. Figure 4-32 shows the principle of series voltage regulation. Notice that the regulator is in series with the load resistance (R_L) and that the fixed resistor (R_s) is in series with the load resistance.

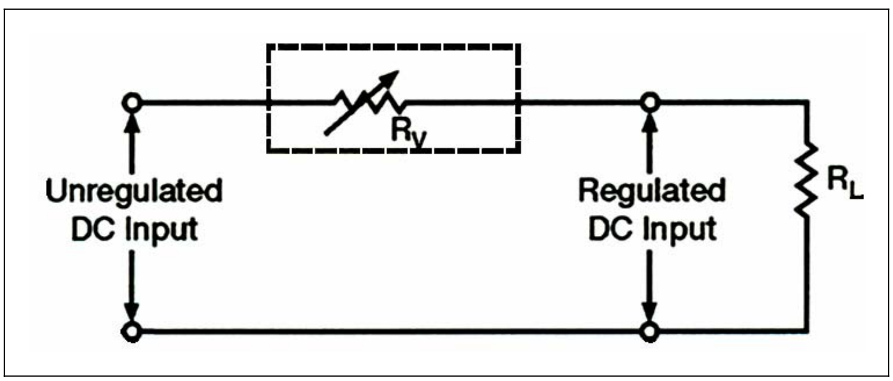


Figure 4-32. Principle of Series Voltage Regulator

4-99. Remember that the voltage drop across a fixed resistor remains constant unless the current flowing through it varies (increases or decreases). In a shunt regulator, see Figure 4-33, output voltage regulation is determined by the current through the parallel resistance of the regulating device (R_V), the load resistance (R_L), and the series resistor (R_s). Assume that the circuit is operating under normal conditions, that the input is 120 volts DC and that the desired regulated output is 100 volts DC. For a 100-volt output to be maintained, 20 volts must be dropped across the series resistor (R_s). If you assume that the value of R_s is 2

ohms, then you must have 10 amperes of current across R_V and R_L. Remember that E = IR. If the values of the resistance of R_V and R_L are equal, then 5 amperes of current will flow through each resistance (R_V and R_L).

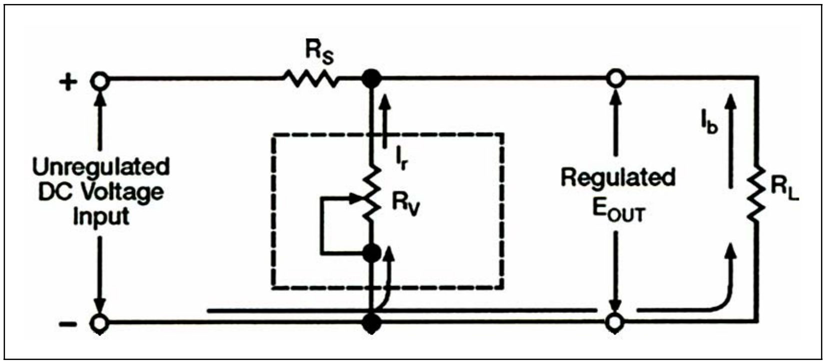


Figure 4-33. Shunt Voltage Regulator (Determining Output Voltage Regulation)

4-100. If the load resistance (R_L) increases, the current through R_L will decrease. For example, assume that the current through R_L is now 4 amperes and that the total current across R_s is 9 amperes. With this drop in current, the voltage drop across R_s is 18 volts. Consequently, the output of the regulator has increased to 102 volts. At this time, the regulating device (R_V) decreases in resistance and 6 amperes of current flows through this resistance (R_V). The total current R_s is once again 10 amperes (6 amperes across R_V and 4 amperes across R_L). Therefore, 20 volts is dropped across R_s causing the output to decrease back to 100 volts. You should know by now that if the load resistance (R_L) increases, the regulating device (R_V) decreases its resistance to compensate for the change. If R_L decreases, the opposite effect occurs and R_V increases.

4-101. Now consider the circuit when a decrease in load resistance takes place. When R_L decreases, the current through R_L subsequently increases to 6 amperes. This action causes a total of 11 amperes to flow through R_s, which then drops 22 volts. As a result, the output is 98 volts. However, the regulating device (R_V) senses this change and increases its resistance so that less current (4 amperes) flows through R_V. The total current again becomes 10 amperes and the output is again 100 volts.

4-102. From these examples, you should know that the shunt regulator maintains the desired output voltage by doing the following:

- Sensing the current change in the parallel resistance of the circuit.
- Compensating for the change.

4-103. Refer to Figure 4-33 to consider how the voltage regulator operates to compensate for changes in input voltages. Remember that the input voltage may vary. Any variation must be compensated for by the regulating device. If an increase in input voltage occurs, the resistance of R_V automatically decreases to maintain the correct voltage division between R_V and R_s. Therefore, notice that the regulator operates in the opposite way to compensate for a decrease in input voltage.

4-104. So far only voltage regulators that use variable resistors have been explained. However, this type of regulation has limitations. Obviously, the variable resistor cannot be adjusted rapidly enough to compensate for frequent fluctuations in voltages. Since input voltages fluctuate frequently and rapidly, the variable resistor is not a practical method for voltage regulation. A voltage regulator that operates continuously and automatically to regulate the output voltage without external manipulation is required for practical regulation.

4-105. Figure 4-34 shows a schematic for a typical series voltage regulator. Notice that this regulator has a transistor (Q1) in the place of the variable resistor found in Figure 4-33. Since the total load current passes through this transistor, it is sometimes called a "pass transistor." Other components that make up the circuit are the current limiting resistor (R1) and the Zener diode (CR1).

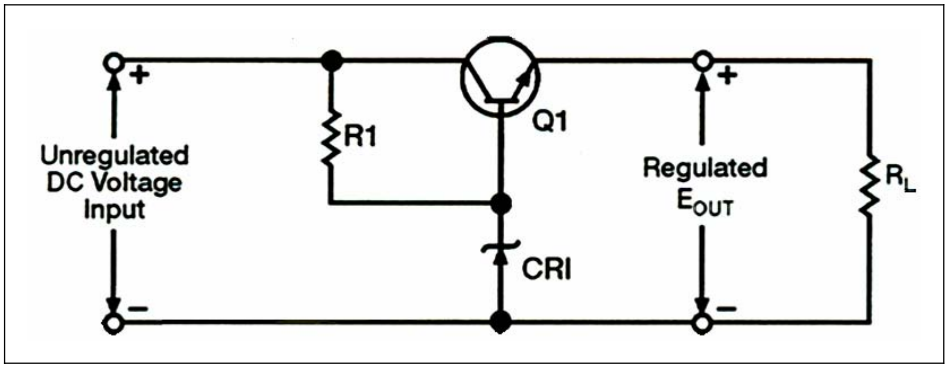


Figure 4-34. Schematic of Series Voltage Regulator

4-106. Remember that a Zener diode blocks current until a specified voltage is applied. Also that the applied voltage is called the breakdown or Zener voltage. Zener diodes are available with different Zener voltages. When the Zener voltage is reached, the Zener diode conducts from its anode to its cathode (with the direction of the arrow).

4-107. In this voltage regulator, Q1 has a constant voltage applied to its base. This voltage is often called the reference voltage. As changes in the circuit output voltage occur, they are sensed at the emitter of Q1, producing a corresponding change in the forward bias of the transistor. In other words, Q1 compensates by increasing or decreasing its resistance in order to change the circuit voltage division.

4-108. In Figure 4-35, voltages are shown to help you understand how the regulator operates. The Zener used in this regulator is a 15-volt Zener. In this instance, the Zener or breakdown voltage is 15 volts. The Zener establishes the value of the base voltage for Q1. The output voltage will equal the Zener voltage minus a 0.7-volt drop across the forward biased base-emitter junction of Q1 or 14.3 volts. Since the output voltage is 14.3 volts, the voltage drop across Q1 must be 5.7 volts.

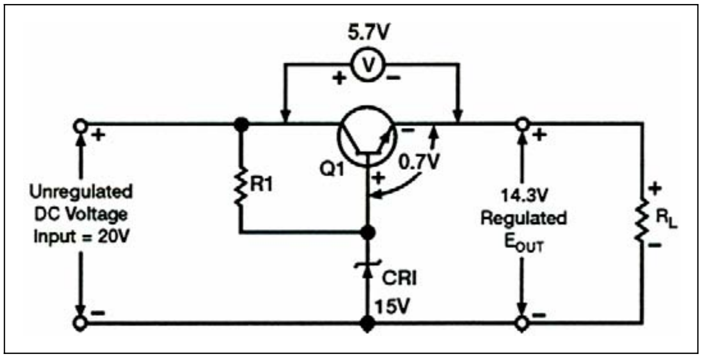


Figure 4-35. Series Voltage Regulator (With Voltages)

4-109. Figure 4-36, view (A), shows what happens when the input voltage exceeds 20 volts. Notice the input and output voltages of 20.1 and 14.4 volts, respectively. The 14.4 output voltage is a momentary deviation, or variation, from the required regulated output voltage of 14.3 and is the result of a rise in the input voltage to 20.1 volts. Since the base voltage of Q1 is held at 15 volts by CR1, the forward bias of Q1 changes to 0.6 volts. Since this bias voltage is less than the normal 0.7 volts, the resistance of Q1 increases, thereby increasing the voltage drop across the transistor to 5.8 volts. This voltage drop restores the output voltage to 14.3 volts. The entire cycle takes only a fraction of a second. Therefore, the change is not visible on an oscilloscope or readily measurable with other standard test equipment.

4-110. Figure 4-36, view (B) shows a schematic diagram for the same series voltage regulator with one significant difference. The output voltage is shown as 14.2 volts instead of the desired 14.3 volts. In this case, the load has increased causing a greater voltage drop across R_L to 14.2 volts. When the output decreases, the forward bias of Q1 increases to 0.8 volts because Zener diode CR1 maintains the base voltage of Q1 at 15 volts. This 0.8 volts is the difference between the Zener reference voltage of 15 volts and the momentary output voltage. (15 V - 14.2 V = 0.8 V). At this point, the larger forward bias on Q1 causes the resistance of Q1 to decrease, thereby causing the voltage drop across Q1 to return to 5.7 volts. This then causes the output voltage to return to 14.3 volts.

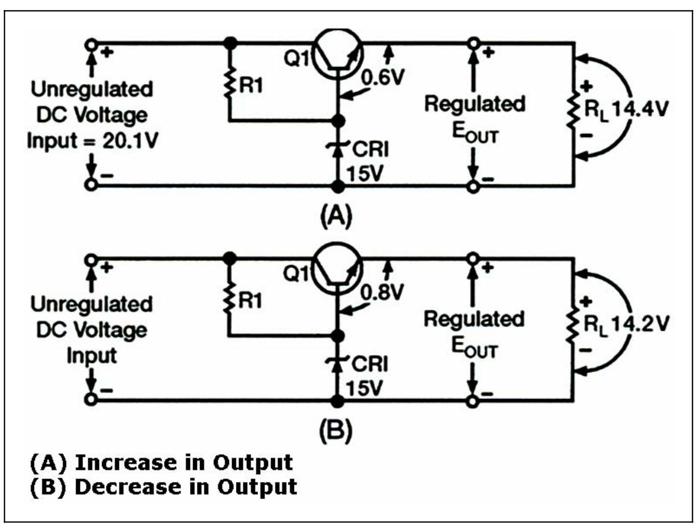


Figure 4-36. Series Voltage Regulator (Input and Output Voltages)

4-111. Figure 4-37 is the schematic of a shunt voltage regulator. Notice that Q1 is in parallel with the load. Components of this circuit are identical with those of the series voltage regulator except for the addition of fixed resistor R_S. Notice in this schematic that this resistor is connected in series with the output load resistance. The current limiting resistor (R1) and Zener diode (CR1) provide a constant reference voltage for the base-collector junction of Q1. The voltage drop across R_S and R1 determines the bias of Q1. Remember, the amount of forward bias across a transistor affects its total resistance. In this case, the voltage drop across R_S is the key to the total circuit operation.

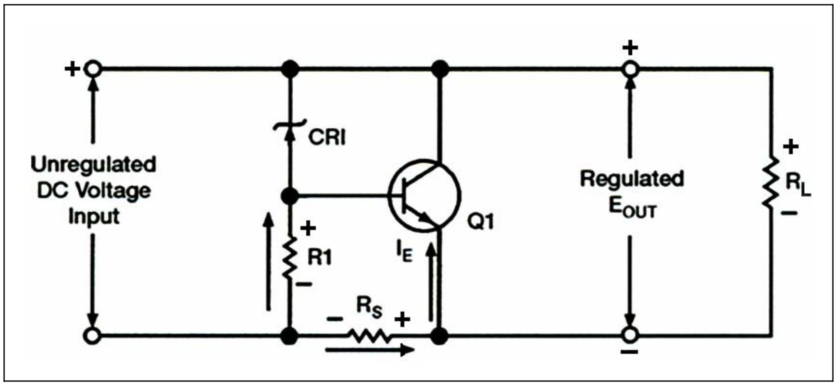


Figure 4-37. Schematic of Shunt Voltage Regulator

4-112. Figure 4-38 is the schematic for a typical shunt-type regulator. Notice that the schematic is identical to the schematic shown in Figure 4-37 except that voltages are shown to help you understand the functions of the various components. In the circuit shown, the voltage drop across the Zener diode (CR1) remains constant at 5.6 volts. This means that with a 20-volt input voltage, the voltage drop across R1 is 14.4 volts. With a base-emitter voltage of 0.7 volts, the output voltage is equal to the sum of the voltages across CR1 and the voltage at the base-emitter junction of Q1. In this example, with an output voltage of 6.3 volts and a 20-volt input voltage, the voltage drop across R_S equals 13.7 volts. Study the schematic to understand fully how these voltages are developed.

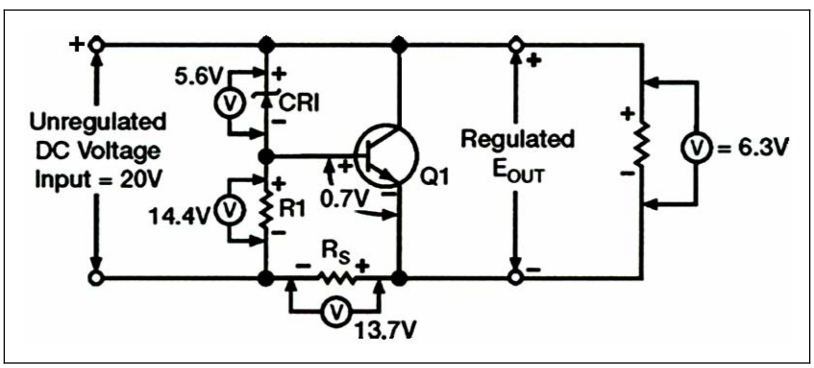


Figure 4-38. Shunt Voltage Regulator (With Voltages)

4-113. Figure 4-39, view (A) shows the same schematic diagram of the shunt voltage regulator shown in Figure 4-38. The difference is that this view shows an increased input voltage of 20.1 volts. This increases the forward bias on Q1 to 0.8 volts. Remember that the voltage drop across CR1 remains constant at 5.6 volts. Since the output voltage is made up of the Zener voltage and the base-emitter voltage, the output voltage momentarily

increases to 6.4 volts. At this time, the increase in the forward bias of Q1 lowers the resistance of the transistor allowing more current to flow through it. Since this current must also pass through R_S, there is also an increase in the voltage drop across this resistor. The voltage drop across R_S is now 13.8 volts and therefore the output voltage is reduced to 6.3 volts. Remember, this change takes place in a fraction of a second.

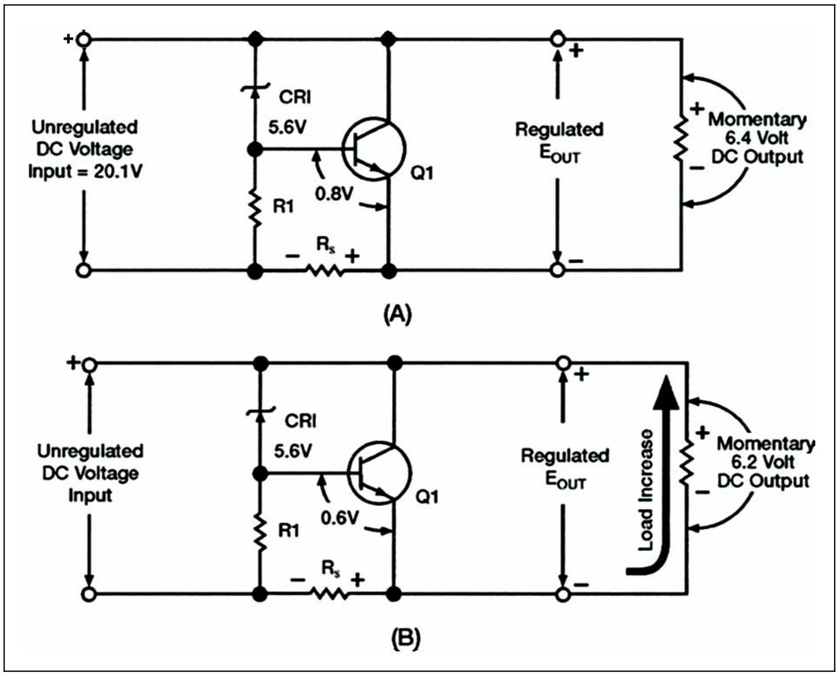


Figure 4-39. Shunt Voltage Regulator (Increased Input Voltage)

4-114. Figure 4-39, view (B) shows the same schematic of the shunt voltage regulator shown in Figure 4-38. The difference is that this view shows a different output voltage. The load current has increased causing a momentary drop in voltage output to 6.2 volts. Remember that the circuit was designed to ensure a constant output voltage of 6.3 volts. Since the output voltage is less than that required, changes occur in the regulator to restore the output to 6.3 volts. Because of the 0.1-volt drop in the output voltage, the forward bias of Q1 is now 0.6 volts. This decrease in the forward bias increases the resistance of the transistor, thereby reducing the current flow through Q1 by the same amount that the load current increased. The current flow through R_S returns to its normal value and restores the output voltage to 6.3 volts.

Current Voltage Regulators

4-115. Remember that voltage regulators work to provide constant output voltages. In some circuits it may be necessary to regulate the current output. The circuitry that provides a constant current output is called a constant current regulator or just CURRENT REGULATOR. Figure 4-40 shows a simplified schematic for a current regulator. The variable resistor shown on the schematic is used to show the concept of current regulation.

4-116. Remember that a variable resistor does not respond quickly enough to compensate for the changes. Notice that an ammeter has been included in this circuit to indicate that the circuit shown is that of a current regulator. When the circuit functions properly, the current reading of the ammeter remains constant. In this case, the variable resistor (R_V) compensates for changes in the load or DC input voltage. Adequate current regulation

results in the loss of voltage regulation. Studying the schematic in Figure 4-40, you should remember that any increase in load resistance causes a drop in current. To maintain a constant current flow, the resistance of R_V must be reduced whenever the load resistance increases. This causes the total resistance to remain constant. An increase in the input voltage must be compensated for by an increase in the resistance of R_V, thereby maintaining a constant current flow. The operation of a current regulator is similar to that of a voltage regulator. The basic difference is that one regulates current and the other regulates voltage.

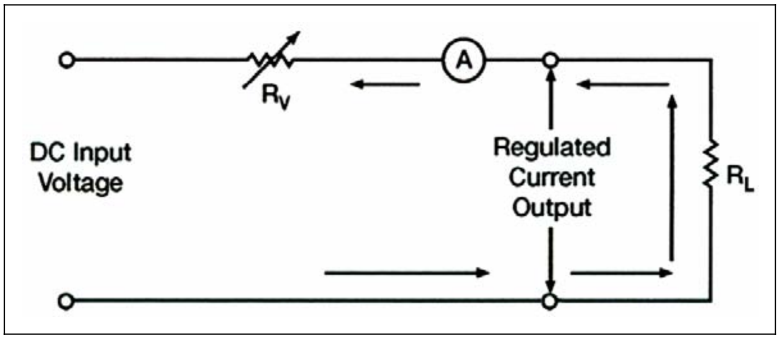


Figure 4-40. Schematic of Current Voltage Regulator

4-117. Since use of a variable resistor is not a practical way to control current fluctuation, or variation, a transistor and a Zener diode (together with necessary resistors) are used. Remember that the Zener diode provides a constant reference voltage. Figure 4-41 shows the schematic of a current regulator circuit. Except for the addition of R1, the circuit shown is similar to that of a series voltage regulator. The resistor is connected in series with the load and senses any current changes in the load. Notice the voltage drop across R1 and the negative voltage polarity applied to the emitter of Q1. The voltage polarity is a result of current flowing through R1 and this negative voltage opposes the forward bias for Q1. However, since the regulated voltage across CR1 has an opposite polarity, the actual bias of the transistor is the difference between the two voltages. Therefore, the purpose of R2 is to function as a current-limiting resistor for the Zener diode.

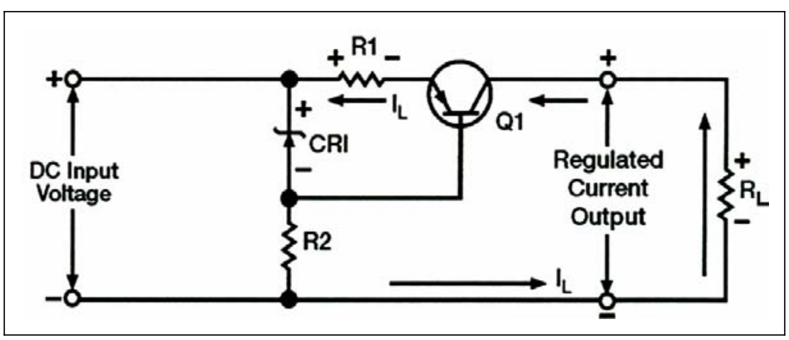


Figure 4-41. Current Voltage Regulator Circuit

4-118. The purpose of a current regulator is to provide a constant current regardless of changes in the input voltage or load current. Figure 4-42 shows the schematic of a circuit designed to provide a constant current of 400 milliamperes. Voltmeters are shown in the schematic to emphasize the voltage drops across specific components. These voltages will help you understand how the current regulator operates. The voltage drop across the base-

emitter junction of Q1 is 0.6 volts. This voltage is the difference between the Zener voltage and the voltage drop across R1. The 0.6-volt forward bias of Q1 permits proper operation of the transistor. The output voltage across R_L is 6 volts as shown by the voltmeter. With a regulated current output of 400 milliamperes, the transistor resistance (R_{Q1}) is 9 ohms. This can be computed by using Ohm's law and the values shown on the schematic. In this case, current (I) is equal to the voltage (E) drop divided by the resistance (R). Therefore 12 volts divided by 30 ohms equals 0.4 ampere, or 400 milliamperes.

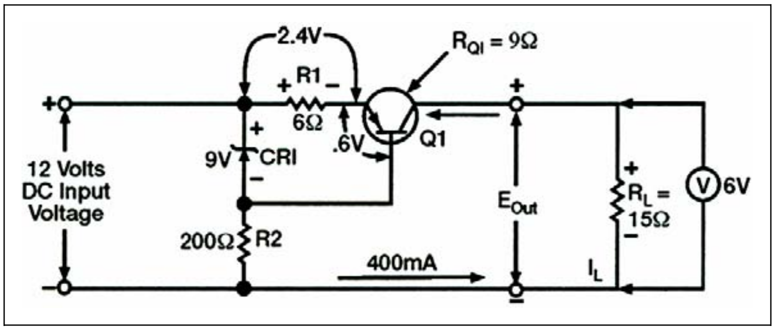


Figure 4-42. Current Voltage Regulator (With Circuit Values)

4-119. Knowing about the basic current regulating circuitry will help you understand how the various components work to maintain the constant 400-milliampere output. Remember a decrease in load resistance causes a corresponding increase in current flow. Figure 4-43 shows that the load resistance R_L has dropped from 15 ohms to 10 ohms. This results in a larger voltage drop across R1 because of the increased current flow. The voltage drop has increased from 2.4 volts to 2.5 volts. Of course, the voltage drop across CR1 remains constant at 9 volts due to its regulating ability. Because of the increased voltage drop across R1, the forward bias on Q1 is now 0.5 volts. Since the forward bias of Q1 has decreased, the resistance of the transistor increases from 9 ohms to 14 ohms. Notice that the 5-ohm increase in resistance across the transistor corresponds to the 5-ohm decrease in the load resistance. Therefore, the total resistance around the outside loop of the circuit remains constant. Since the circuit is a current regulator, you know that output voltages will vary as the regulator maintains a constant current output. In Figure 4-43, the voltage output is reduced to 4 volts, which is computed by multiplying current (I) times resistance (R) (400 mA x 10 ohms = 4 volts).

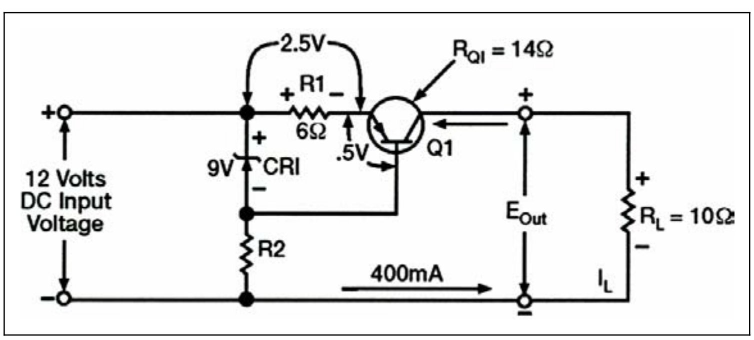


Figure 4-43. Current Voltage Regulator (With a Decrease in R_L)

VOLTAGE MULTIPLIERS

4-120. Another method for increasing voltages is known as voltage multiplication. VOLTAGE MULTIPLIERS are used primarily to develop high voltages where low current is required. The most common application of the high voltage outputs of voltage multipliers is the anode of CRTs that are used for radarscope presentations, oscilloscope presentations, or TV picture tubes. The DC output of the voltage multiplier ranges from 1,000 volts to 30,000 volts. The actual voltage depends upon the size of the CRT and its equipment application.

4-121. Voltage multipliers may also be used as primary power supplies where a 177-volt AC input is rectified to pulsating DC. This DC output voltage may be increased (through use of a voltage multiplier) to as much as 1,000 volts DC. This voltage is generally used as the plate or screen grid voltage for electron tubes.

4-122. Remember, when voltage is stepped up the output current decreases. This is also true of voltage multipliers. Although the measured output voltage of a voltage multiplier may be several times greater than the input voltage, once a load is connected the value of the output voltage decreases. Any small fluctuation of load impedance also causes a large fluctuation in the output voltage of the multiplier. For this reason, voltage multipliers are used only in special applications where the load is constant and has high impedance or where input voltage stability is not critical.

4-123. Voltage multipliers may be classified as voltage doublers, triplers, or quadruplers. The classification depends on the ratio of the output voltage to the input voltage. For example, a voltage multiplier that increases the peak input voltage twice is called a voltage doubler. Voltage multipliers increase voltages through the use of series-aiding voltage sources. This can be compared to the connection of dry cells (batteries) in series. The figures used in the explanation of voltage multipliers show a transformer input, even though for some applications a transformer is not necessary. The input could be directly from the power source or line voltage. This, of course, does not isolate the equipment from the line and creates a potentially hazardous condition. Most military equipment uses transformers to reduce this hazard.

4-124. Figure 4-44 shows the schematic for a half-wave voltage doubler. Notice the similarities between this schematic and those of half-wave voltage rectifiers with which you are already familiar. In fact, the doubler shown is made up of two half-wave voltage rectifiers (C1 and CR1 make up one half-wave rectifier and C2 and CR2 make up the other).

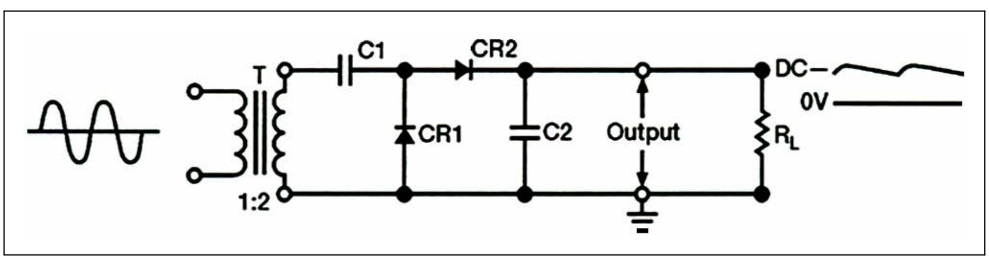


Figure 4-44. Half-wave Voltage Doubler

4-125. The dark lines in Figure 4-45, view (A) show the schematic of the first half-wave rectifier. The dotted lines and associated components represent the other half-wave rectifier and load resistor. Notice that C1 and CR1 works exactly like a half-wave rectifier. During

the positive alternation of the input cycle (Figure 4-45, view A), the polarity across the secondary winding of the transformer is as shown. Notice that the top of the secondary is negative. At this time, CR1 is forward biased (cathode negative in respect to the anode). This forward bias causes CR1 to function like a closed switch and allows current to follow the path indicated by the arrows. Also at this time, C1 charges to the peak value of the input voltage, or 200 volts, with the polarity shown.

4-126. During the period when the input cycle is negative (Figure 4-45, view (B)), the polarity across the secondary of the transformer is reversed. Notice specifically that the top of the secondary winding is now positive. This condition now forward biases CR2 and reverse biases CR1. A series circuit now exists consisting of C1, CR2, C2, and the secondary of the transformer. The arrows indicate the current flow. The secondary voltage of the transformer now aids the voltage on C1. This results in a pulsating DC voltage of 400 volts, as shown by the waveform. The effect of series aiding is almost the same as the connection of two 200-volt batteries in series. Figure 4-46 shows the C2 charges to the sum of these voltages, or 400 volts.

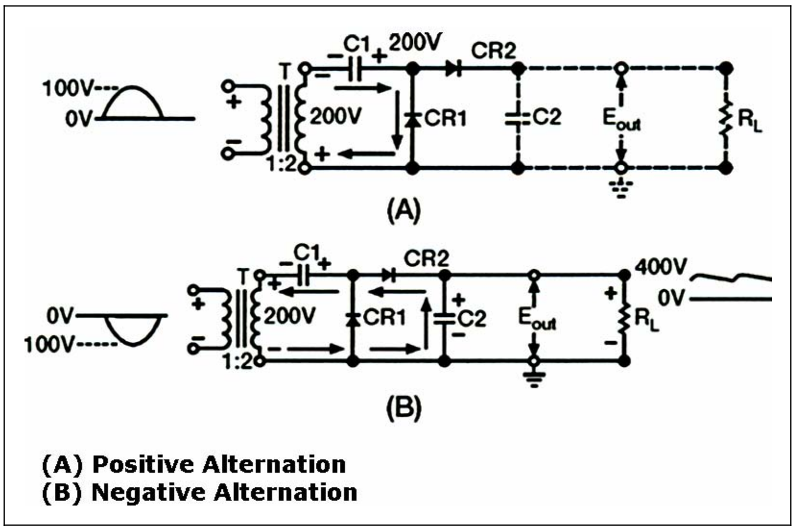


Figure 4-45. Rectifier Action of CR1 and CR2

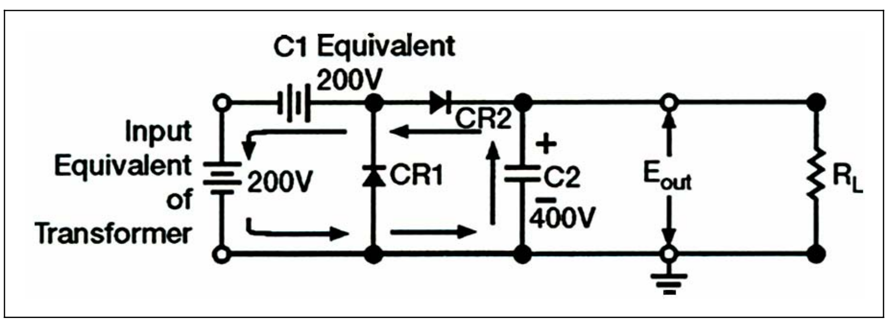


Figure 4-46. Series-aiding Sources

4-127. Figure 4-47 shows the schematic of a half-wave voltage tripler. When comparing Figures 4-46 and 4-47, you should see that the circuitry is identical except for the additional parts, components, and circuitry shown by the dotted lines (CR3, C3, and R2 make up the additional circuitry). By themselves, CR3, C3, and R2 make up a half-wave

rectifier. Of course, if you remove the added circuitry, you will once again have a half-wave voltage doubler.

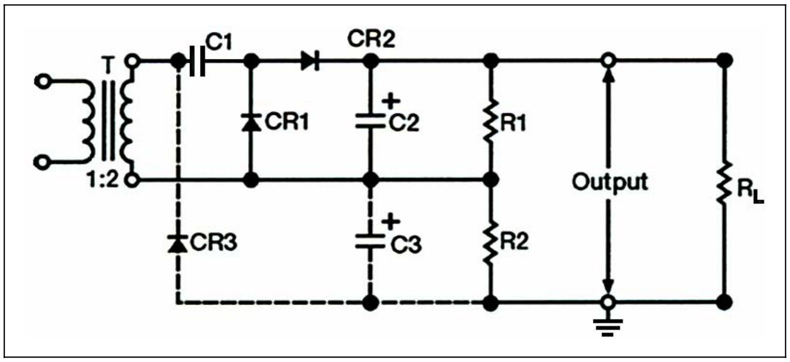


Figure 4-47. Half-wave Voltage Tripler

4-128. Figure 4-48, view (A) shows the schematic for the voltage tripler. Notice that CR3 is forward biased and functions like a closed switch. This allows C3 to charge to a peak voltage of 200 volts at the same time C1 is also charging to 200 volts.

4-129. Figure 4-48, view (B) shows the other half of the input cycle. C2 is charged to twice the input voltage, or 400 volts, as a result of the voltage-doubling action of the transformer and C1. At this time, C2 and C3 are used as series-aiding devices and the output voltage increases to the sum of their respective voltages, or 600 volts. R1 and R2 are proportional according to the voltages across C2 and C3. In this case, there is a 2 to 1 ratio.

4-130. Figure 4-49 shows the circuit of a full-wave voltage doubler. The main advantage of a full-wave doubler over a half-wave doubler is better voltage regulation. There is better voltage regulation because of a result of reduction in the output ripple amplitude and an increase in the ripple frequency. The circuit is, in fact, two half-wave rectifiers. These rectifiers function as series-aiding devices except in a slightly different way. During the alternation when the secondary of the transformer is positive at the top, C1 charges to 200 volts through CR1. Then, when the transformer secondary is negative at the top, C2 charges to 200 volts through CR2. R1 and R2 are equal value, balancing resistors that stabilize the charges of the two capacitors. Resistive load R_L is connected across C1 and C2 so that R_L receives the total charge of both capacitors. The output voltage is +400 volts, when measured at the top of R_L, or point "A" with respect to point "B." If the output is measured at the bottom of R_L, it is -400 volts. Either way, the output is twice the peak value of the AC secondary voltage. Therefore, the possibilities for voltage multiplication are almost unlimited.

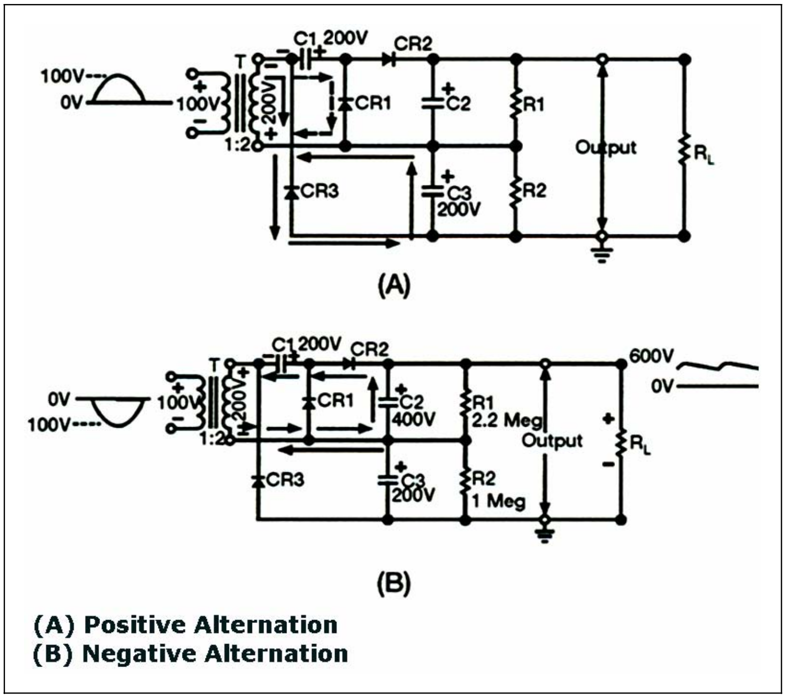


Figure 4-48. Voltage Tripler

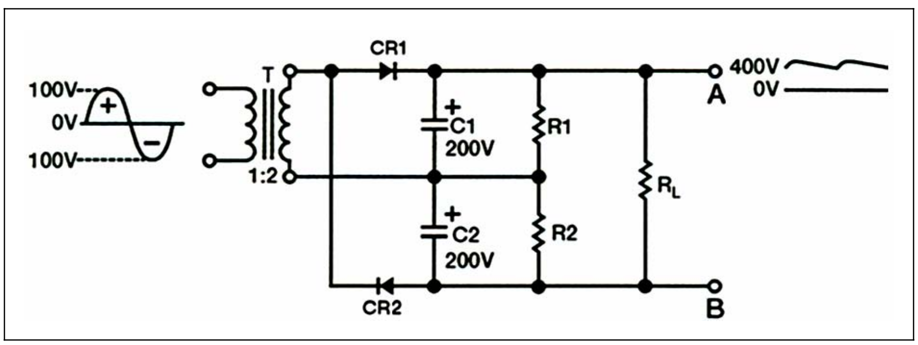


Figure 4-49. Full-wave Voltage Doubler

SHORT CIRCUIT PROTECTION

4-131. The main disadvantage of a series regulator is that the pass transistor is in series with the load. If a short develops in the load, a large amount of current will flow in the regulator circuit. The pass transistor can be damaged by this excessive current flow. You can place a fuse in the circuit, but in many cases, the transistor will be damaged before the fuse blows. The best way to protect this circuit is to limit the current automatically to a safe value. Figure 4-50 shows a series regulator with a current-limiting circuit. You should remember that in order for a silicon NPN transistor to conduct, the base must be between 0.6 volts to 0.7 volts more positive than the emitter. Resistor R4 will develop a voltage drop of 0.6 volts when the load current reaches 600 milliamperes. This is shown by using Ohm's law:

$$I = \frac{E}{R} = \frac{0.6\text{volt}}{1\text{ ohm}} = .6 \text{ amphere or 600 milliamperes}$$

4-132. When load current is below 600 milliamperes, the base-to-emitter voltage on Q2 is not high enough to allow Q2 to conduct. With Q2 cut off, the circuit acts like a series regulator. When the load current increases above 600 milliamperes, the voltage drop across R4 increases to more than 0.6 volts. This causes Q2 to conduct through resistor R2, thereby decreasing the voltage on the base of pass transistor Q1. This action causes Q1 to conduct less. Therefore, the current cannot increase above 600 to 700 milliamperes.

4-133. By increasing the value of R4, you can limit the current to almost any value. For example, a 100-ohm resistor develops a voltage drop of 0.6 volts at 6 milliamperes of current. You may encounter current-limiting circuits that are more sophisticated, but the theory of operation is always the same. So, if you understand this circuit, you should have no problems with the others.

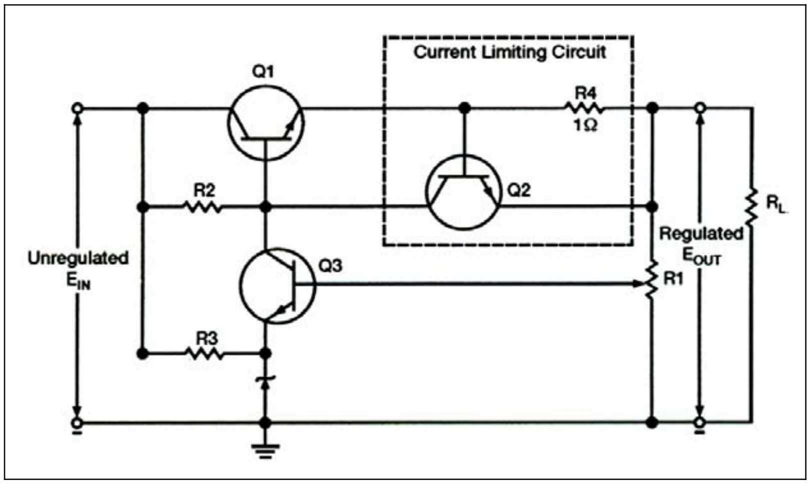


Figure 4-50. Series Regulator With Current Limiting

TROUBLESHOOTING POWER SUPPLIES

4-134. There are safety precautions that are very important to remember whenever you are working with electricity. In the front of all ETMs, you will find a section on safety precautions. There should also be a sign posted on each piece of equipment listing the specific precautions for that equipment. One area that is sometimes overlooked and is a hazard is the method in which equipment is grounded. By grounding the return side of the power transformer to the metal chassis, the load being supplied by the power supply can be wired directly to the metal chassis. Therefore, the necessity of wiring directly to the return side of the transformer is eliminated. This method saves wire and reduces the cost of building the equipment. While it solves one of the problems of the manufacturer, it also creates a problem for you. Observe the following precautions before starting to work on any electronic or electrical equipment.

PRECAUTIONS

- Always ensure that the equipment and any test equipment you are using are properly grounded.
- Inspect the rubber mat you will be standing on to ensure it is in good condition.

As long as you follow these precautions, you should be able to avoid the possibility of becoming an electrical conductor.

TESTING ELECTRONIC EQUIPMENT

4-135. The two most widely used checks in testing electronic equipment are VISUAL and SIGNAL TRACING. The importance of the visual check should not be underestimated because defects can be found right away, simply by looking for them. A visual check does not take long; in fact, you should be able to see the problem in about two minutes if it is the kind of problem that is visible. Learn the visual check procedures found in Table 4-2 because you will find yourself using them quite often. This procedure is not only good for power supplies but also for any type of electronic equipment you may be troubleshooting.

Table 4-2. Visual Check Procedures

BEFORE YOU PLUG IN THE EQUIPMENT, LOOK FOR:
SHORTS - Any terminal or connection that is close to the chassis or to any other terminal should be examined for the possibility of a short. A short in any part of the power supply can cause considerable damage. Look for and remove any stray drops of solder, bits of wire, nuts, or screws. It sometimes helps to shake the chassis and listen for any sounds of rattling. Remember to correct any problem that may cause a short circuit. Even though it is not causing trouble now, fix it; it may cause problems in the future.
DISCOLORED OR LEAKING TRANSFORMER - This is a sure sign that there is a short somewhere. Locate the short. If the equipment has a fuse, find out why the fuse did not blow. Sometimes a fuse that is too large may have been installed or there may be a short across the fuse holder.
LOOSE, BROKEN, OR CORRODED CONNECTIONS - Any connection that is not in good condition is a trouble spot. Even if it is not causing trouble now, fix it; it will probably cause problems in the future.
DAMAGED RESISTORS OR CAPACITORS - A resistor that is discolored or charred has been subjected to an overload. An electrolytic capacitor will show a whitish deposit at the seal around the terminals. Check for a short whenever you notice a damaged resistor or a damaged capacitor. If there is no short, the trouble may be that the power supply has been overloaded in some way. Make a note to replace the part after signal tracing. There is no sense in using a new part until the trouble has been located.
AFTER YOU PLUG IN THE POWER SUPPLY, LOOK FOR:
SMOKING PARTS - If any part smokes or if you hear any boiling or sputtering sounds, pull the plug immediately. There is a short circuit somewhere that you have missed in your first inspection. Use an ohmmeter to check the part once again. Start in the neighborhood of the smoking part.
SPARKING - Tap or shake the chassis. If you see or hear sparking, you have located a loose connection or a short. Check and repair.

4-136. If you locate and repair any of the defects listed in Table 4-2, make a note of what you find and what you did to correct the defect. It is quite probable you have found the trouble. However, you must not take anything for granted. You must prove to yourself that the equipment is operating properly and that no other troubles exist.

4-137. If you find none of the defects listed in Table 4-2, go ahead with the signal tracing procedure. The trouble is probably of such a nature that it cannot be seen directly with your eye, but only be seen through the oscilloscope.

4-138. Tracing the AC signal through the equipment is the most rapid and accurate method of locating a trouble that cannot be found by a visual check. It also serves as a check on any repairs you may have made. The idea is to trace the AC voltage from the transformer, to see it change to pulsating DC at the rectifier output, and then to see the pulsations smoothed out by the filter. The point where the signal stops or becomes distorted is the place to look for the trouble. If you have no DC output voltage, you should look for an open or a short in your signal tracing. If you have a low DC voltage, you should look for a defective part and keep your eyes open for the place where the signal becomes distorted. Signal tracing is one method used to localize trouble in a circuit. This is done by observing the waveform at the input and output of each part of a circuit.

4-139. Figure 4-51 shows what each part of a good power supply does to a signal. The AC voltage is brought in from the power line by means of the line cord. This voltage is connected to the primary of the transformer through the ON-OFF switch (S1). At the secondary winding of the transformer (points 1 and 2), the scope shows you a picture of the stepped-up voltage developed across each half of the secondary winding (the picture is that of a complete sine wave). Each of the two stepped-up voltages is connected between ground and one of the two anodes of the rectifier diodes. At the two rectifier anodes (points 4 and 5), there is still no change in the shape of the stepped-up voltage (the scope picture still shows a complete sine wave).

4-140. When you look at the scope pattern for point 6 (the voltage at the rectifier cathodes), you see the waveshape for pulsating DC. This pulsating DC is fed through the first choke (L1) and filter capacitor (C1), which remove a large part of the ripple, or “hum,” (as shown by the waveform for point 7). Finally, the DC voltage is fed through the second choke (L2) and filter capacitor (C2) that remove nearly the entire remaining ripple. See the waveform for point 8, which shows almost no visible ripple. You now have almost pure DC. No matter what power supply you use in the future, they all do the same thing and that is that they change AC voltage into DC voltage.

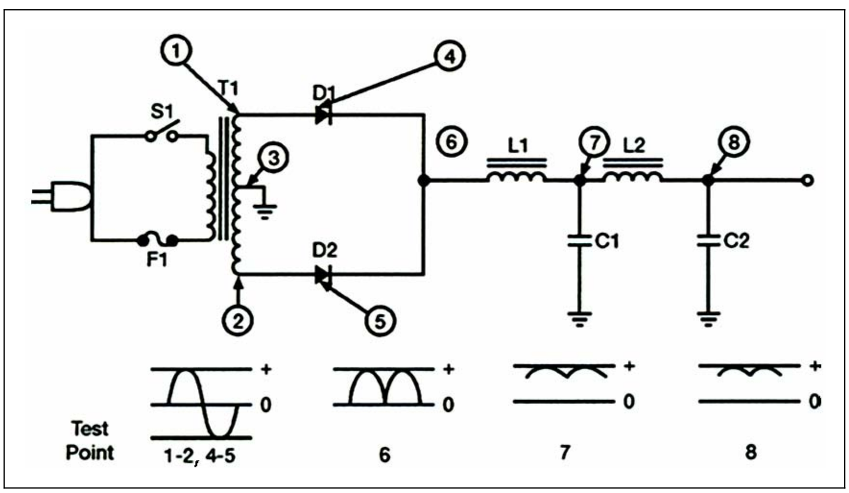


Figure 4-51. Complete Power Supply (Without Regulator)

COMPONENT PROBLEMS

4-141. Many troubles can occur with the many different electronic circuit components. The following describes some of the troubles that can occur.

Transformer and Choke Troubles

4-142. The transformer and the choke are similar in construction. The following (also see Figure 4-52) are the four basic troubles that can develop:

- A winding can open (number 1).
- Two or more turns of one winding can short together (number 2).
- A winding can short to the casing that is usually grounded (number 3).
- Two windings (primary and secondary) can short together (number 4). This trouble is possible only in transformers.

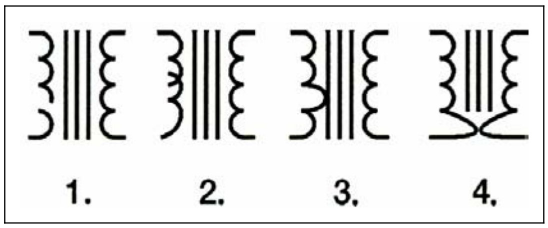


Figure 4-52. Basic Troubles for Transformer and Choke

When you have decided which one of the four is causing the trouble, you have definite steps to take. If you determined that there is an open winding, or windings shorted together or to ground, an ohmmeter continuity check will locate the trouble. If the turns of a winding are shorted together, you may not be able to detect a difference in winding resistance. Therefore, you need to connect a good transformer in the place of the old one and see if the troubles are eliminated. However, keep in mind that transformers are difficult to replace. Make absolutely sure that the trouble is not elsewhere in the circuit before you change the transformer. Sometimes the shorts will only appear when the operating voltages are applied to the transformer. In this case you might find the trouble with a megger (an instrument that applies a high voltage as it reads resistance).

Capacitor Troubles

4-143. The following (also see Figure 4-53) are the two things that can happen to a capacitor:

- It may open up (number 1). This removes the capacitor completely from the circuit.
- It may develop an internal short circuit (number 2). This means that it begins to pass current as though it were a resistor or a direct short.

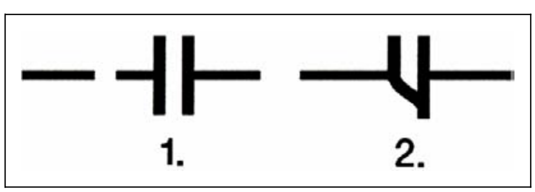


Figure 4-53. Capacitor Troubles

You may check a capacitor suspected of being open by disconnecting it from the circuit and checking it with a capacitor analyzer. You can check a capacitor suspected of being leaky with an ohmmeter. If it reads less than 500 kilohms, it is more than likely bad. However, capacitor troubles are difficult to find since they may appear intermittently or only under operating voltages. Therefore, the best check for a faulty capacitor is to replace it with a good one. If this restores proper operation, the fault was in the capacitor.

Resistor Troubles

4-144. The following (also see Figure 4-54) are the three things that can happen to a resistor:

- It can open (number 1).
- It can increase in value (number 2).
- It can decrease in value (number 3).

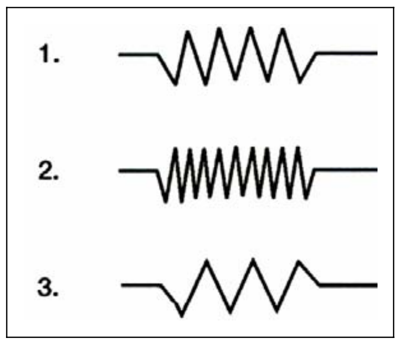


Figure 4-54. Resistor Troubles

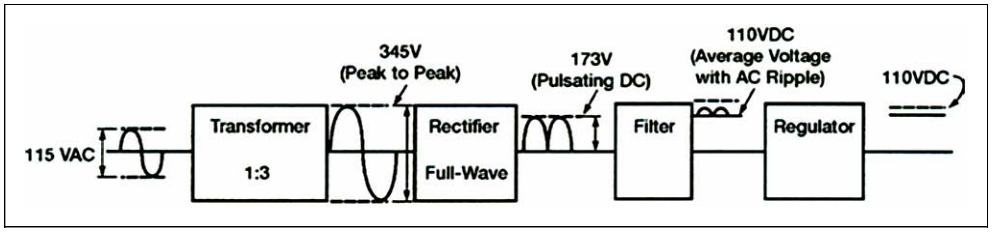
Remember to use an ohmmeter to check possible resistor troubles. Make sure no parallel circuit is connected across the resistor you wish to measure. When you know a parallel circuit is connected across the resistor or when you are in doubt, disconnect one end of the resistor before measuring. The ohmmeter check will usually be adequate. However, never forget that sometimes, intermittent troubles may develop in resistors as well as in any other electronic parts.

4-145. You may observe different problems that have not been covered specifically in this chapter. However, you should have gained enough knowledge to locate and repair any problem that may occur.

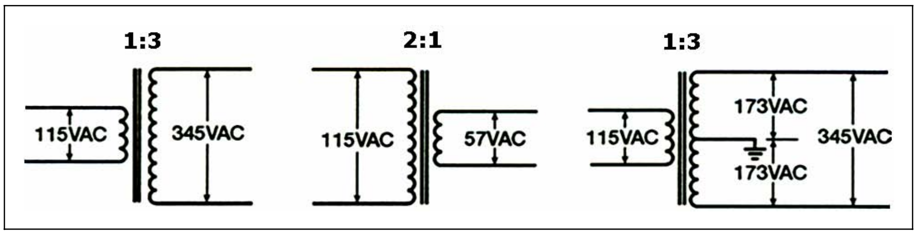
SUMMARY

4-146. Now that we have completed this chapter, the following is a short review of the more important points. Answer the check-on-learning questions, found after the summary, to determine how much you have learned from this chapter.

POWER SUPPLIES - electronic circuits designed to convert AC to DC at any desired level. Almost all power supplies are composed of four sections: transformer, rectifier, filter, and regulator.

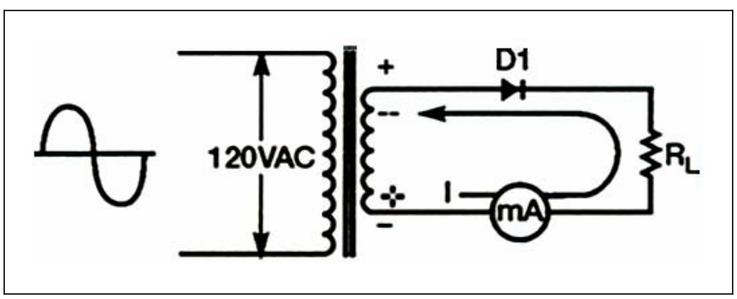


POWER TRANSFORMER - the input transformer for the power supply.

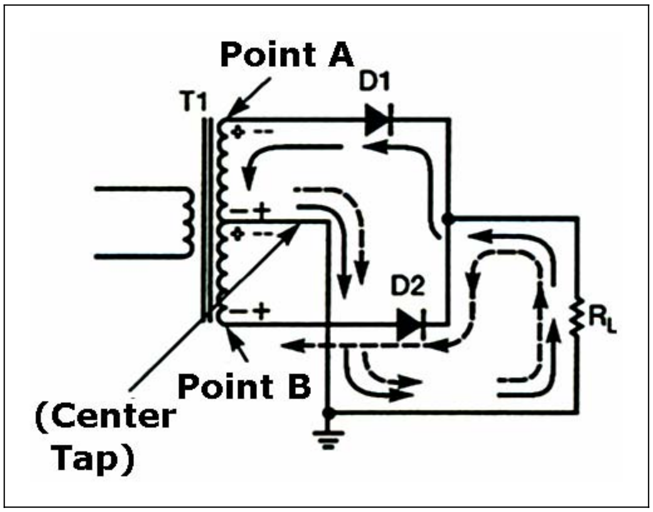


RECTIFIER - the section of the power supply that contains the secondary windings of the power transformer and the rectifier circuit. The rectifier uses the ability of a diode to conduct during one half cycle of AC to convert AC to DC.

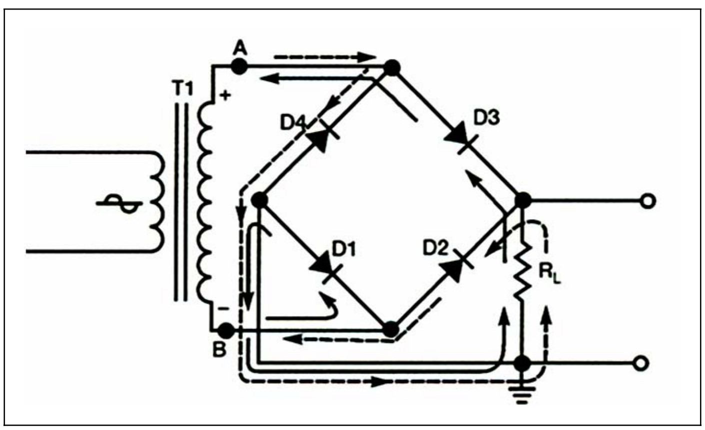
HALF-WAVE RECTIFIERS - gives an output on only one half cycle of the input AC. For this reason, the pulses of DC are separated by a period of one half cycle of zero potential voltage.



***FULL-WAVE RECTIFIERS* -** conducts on both halves of the input AC cycles. As a result, the DC pulses are not separated from each other. A characteristic of full-wave rectifiers is the use of a center-tapped, high-voltage secondary. Because of the center tap, the output of the rectifier is limited to one-half of the input voltage of the high-voltage secondary.

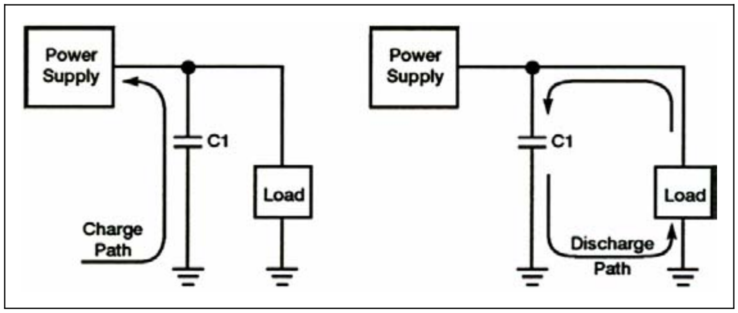


BRIDGE RECTIFIERS - full-wave rectifiers that do not use a center-tapped, high-voltage secondary. Because of this, their DC output voltage is equal to the input voltage from the high-voltage secondary of the power transformer. Bridge rectifiers use four diodes connected in a bridge network. Diodes conduct in diagonal pairs to give a full-wave pulsating DC output.

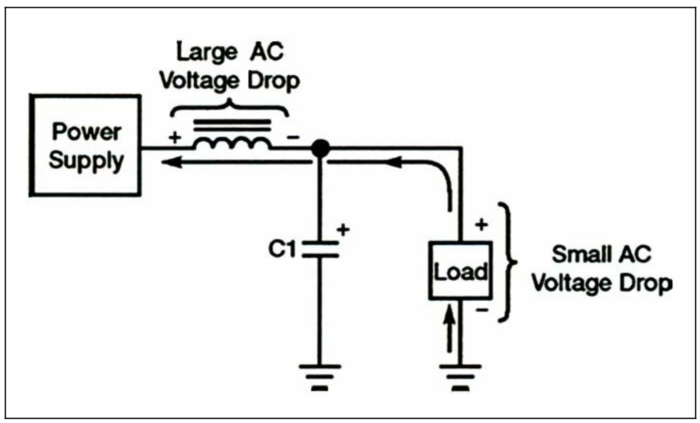


FILTER CIRCUITS - designed to smooth, or filter, the ripple voltage present on the pulsating DC output of the rectifier. An electrical device, that has the ability to store energy and to release the stored energy, can do this.

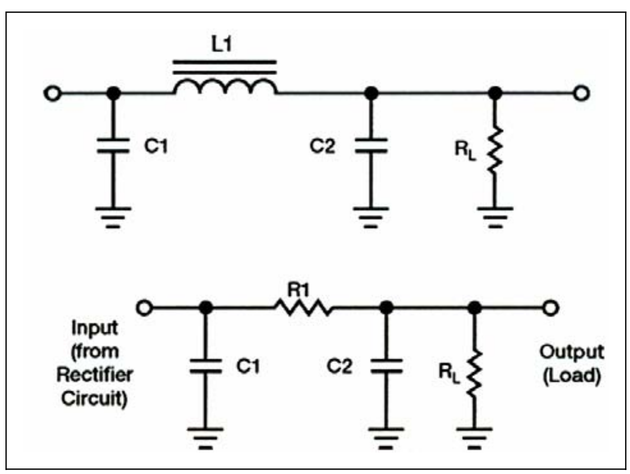
CAPACITANCE FILTERS – these are nothing more than large capacitors placed across the output of the rectifier section. Because of the large size of the capacitors, fast charge paths, and slow discharge paths, the capacitor will charge to average value, which will keep the pulsating DC output from reaching zero volts.



INDUCTOR FILTERS **-** uses an inductor called a choke to filter the pulsating DC input. Because of the impedance offered to circuit current, the output of the filter is at a lower amplitude than the input.

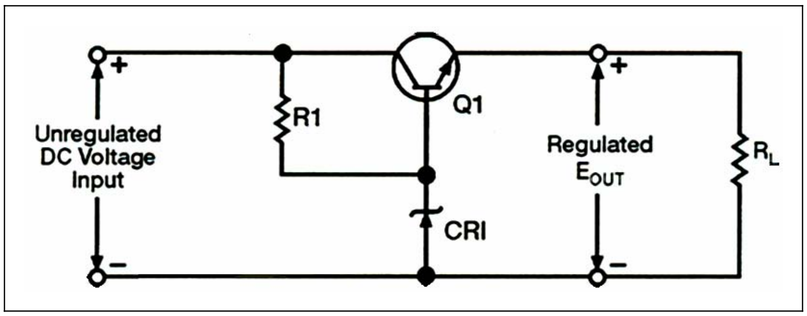


PI-TYPE FILTERS **-** uses capacitive and inductive filters connected in a pi-type configuration. By combining filtering devices, the ability of the pi filter to remove ripple voltage is superior to that of either the capacitance or inductance filter.

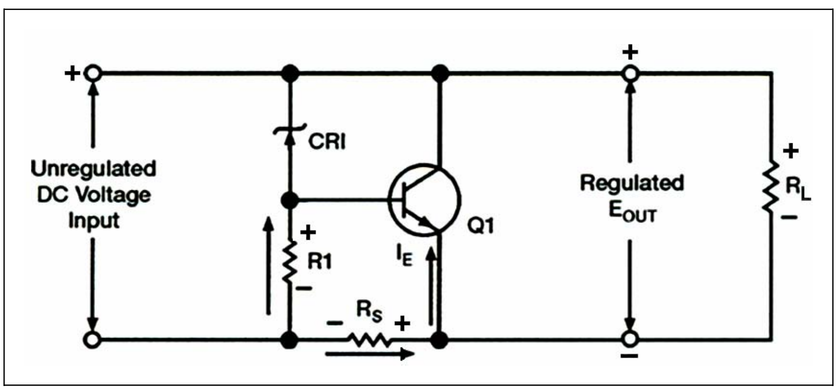


VOLTAGE REGULATORS **-** circuits designed to maintain the output of power supplies at a constant amplitude despite variations of the AC source voltage or changes of the resistance of the load. This is done by creating a voltage divider of a resistive element in the regulator and the resistance of the load. Regulation is achieved by varying the resistance of the resistive element in the regulator.

SERIES REGULATOR **-** uses a variable resistance in series with the load. Regulation is achieved by varying this resistance either to increase or to decrease the voltage drop across the resistive element of the regulator. Characteristically, the resistance of the variable resistance moves in the same direction as the load. When the resistance of the load increases, the variable resistance of the regulator increases; when load resistance decreases, the variable resistance of the regulator decreases.



SHUNT REGULATORS - uses a variable resistance placed in parallel with the load. Regulation is achieved by keeping the resistance of the load constant. Characteristically, the resistance of the shunt moves in the opposite direction of the resistance of the load.



CURRENT LIMITER - a short-circuit protection device that automatically limits the current to a safe value. This is done when the current-limiting transistor senses an increase in load current. At this time the current-limiting transistor decreases the voltage on the base of the pass transistor in the regulator, causing a decrease in its conduction. Therefore, current cannot rise above a safe value.

TROUBLESHOOTING - a method of detecting and repairing problems in electronic equipment. Two methods commonly used are the visual check and signal tracing. The visual check allows a quick check of component problems (such as shorts, discolored or leaky transformers, loose or broken connections, damaged resistors or capacitors, smoking parts, or sparking). The signal tracing method is used when the problem cannot be seen using the visual check. Therefore, test equipment needs to be used to observe the electron signal. Component failure is also important in troubleshooting. In transformers and chokes a winding can open, two or more turns of one winding can short together, a winding can short to the casing that is usually grounded, and windings (primary and secondary) can short together. A capacitor can open up or it may develop an internal short circuit. A resistor can open, increase in value, or decrease in value.

CHAPTER 4
CHECK-ON-LEARNING QUESTIONS

When you are satisfied that you have answered every question to the best of your ability, check your answers using Appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. What are the four basic sections of a power supply?

2. What is the purpose of the rectifier section?

3. What is the purpose of the filter section?

4. What is the purpose of the regulator section?

5. What is the name of the simplest type of rectifier?

6. Is the peak value higher or lower than the RMS value?

7. What is the ripple frequency of a full-wave rectifier with an input frequency of 60 Hz?

8. What is the main disadvantage of the full-wave rectifier?

9. What is the name of the rectifier that has four diodes connected?

10. What main advantage does a bridge rectifier have over a conventional full-wave rectifier?

11. Does a bridge rectifier produce a higher or lower output voltage than the conventional full-wave rectifier circuit?

12. For proper operation, what do most electronic circuits require?

13. Will the X_C increase or decrease if you increase the value of the capacitor?

14. What is produced when there is a change of current through an inductor?

15. In a capacitor filter, is the capacitor in series or in parallel with the load?

16. The value of capacitance and the value of the load resistance determine what for the capacitor?

17. How do you reduce the impedance of the capacitor by one-half?

18. How many times does conduction occur during each cycle for a full-wave rectifier?

19. What is the range of values usually chosen for a choke?

20. The filtering action of the LC choke-input filter is improved when the filter is used in conjunction with what?

21. What protects the filter capacitor in the LC choke-input filter from extreme voltage surges?

22. What must you use at all times when the capacitor is electrolyte?

23. Why would you add a second stage of RC filtering?

24. What is the most commonly used filter?

25. What are the two disadvantages of the LC filter?

26. What results in a leaky or open capacitor in the filter circuit?

27. What should be the ideal output of most power supplies?

28. What is the name of the circuit that maintains constant output voltage?

29. A voltage regulator provides an output voltage with little or no what?

30. What are the two basic types of voltage regulators?

31. A Zener diode does what until a specified voltage is applied?

32. What is the purpose of a current regulator?

33. What is the range of the DC output of the voltage multiplier?

34. What is the main advantage of a full-wave doubler over a half-wave doubler?

35. A half-wave voltage doubler is made up of how many half-wave rectifiers?

36. What is the main disadvantage of a series regulator?

37. What is the main reason for grounding the return side of the transformer to the chassis?

38. What are the two types of checks used in testing electronic equipment?

Chapter 5
Amplifiers

LEARNING OBJECTIVES

Learning objectives serve as a preview of the information you are expected to learn in this chapter. The comprehensive check-on-learning questions, found at the end of the chapter, are based on the objectives. Upon completion of this chapter, you will be able to perform the following learning objectives:

- Define amplification, list several common uses, and state two ways in which amplifiers are classified.
- List the four classes of operation for an amplifier.
- List the four ways of coupling signals into and out of amplifier circuits.
- Name the impedance characteristics of the three configurations of a transistor amplifier.
- Define feedback and list the two types feedback.
- Describe and state one use for a phase splitter.
- State a common use for and one advantage of a push-pull amplifier.

INTRODUCTION TO AMPLIFIERS

5-1. This chapter, along with chapters 6 and 7, are concerned with the circuitry of amplifiers. While components are discussed, the discussion of the components is not an explanation of the working of the component itself, but an explanation of the component as it relates to the circuit.

5-2. The circuits in this chapter are concerned with amplifiers. Amplifiers are devices that provide amplification. That does not explain much, but it does describe an amplifier if you know what amplification is and for what it is used.

AMPLIFICATION PROCESS

5-3. Just as an amplifier is a device that provides amplification, amplification is the process of providing an increase in amplitude. Amplitude is a term that describes the size of a signal. In terms of AC, amplitude usually refers to the amount of voltage or current. A 5-volt peak-to-peak AC signal would be larger in amplitude than a 4-volt peak-to-peak AC signal. "Signal " is a general term used to refer to any AC or DC of interest in a circuit (for example, input signal and output signal). A signal can be large or small, AC or DC, a sine wave or non-sinusoidal, or even non-electrical (such as sound or light). "Signal" is also not very descriptive by itself, but it does sound more technical than the word "thing". It is not very impressive to refer to the "input thing" or the "thing that comes out of this circuit."

5-4. Perhaps the concept of the relationship of amplifier-amplification-amplitude will be clearer if you consider a parallel situation (an analogy). A magnifying glass is a magnifier. As such, it provides magnification, which is an increase in the magnitude (size) of an object. This relationship of magnifier-magnification-magnitude is the same as the relationship of amplifier-amplification-amplitude. The analogy is true in one other aspect

as well. The magnifier does not change the object that is being magnified; it is only the image that is larger, not the object itself. With the amplifier, the output signal differs in amplitude from the input signal, but the input signal still exists unchanged. So, the object (input signal) and the magnifier (amplifier) control the image (output signal).

5-5. An amplifier can be defined as a device that enables an input signal to control an output signal. The output signal will have some (or all) of the characteristics of the input signal but will generally be larger than the input signal in terms of voltage, current, or power.

USES OF AMPLIFICATION

5-6. Most electronic devices use amplifiers to provide various amounts of signal amplification. Since most signals are originally too small to control or drive the desired device, some amplification is needed.

5-7. Figure 5-1 shows an example of the use of an amplifier. In a radio receiver, the signal picked up by the antenna is too weak (small) to be used as it is, so amplification is needed. This signal must be amplified before it is sent to the detector. Each time the signal is amplified it is said to go through a stage of amplification. The detector separates the audio signal from the frequency that was sent by the transmitter. The audio signal from the detector will then be amplified to make it large enough to drive the speaker of the radio. Almost every electronic device contains at least one stage of amplification, so you will be seeing amplifiers in many devices that you work on.

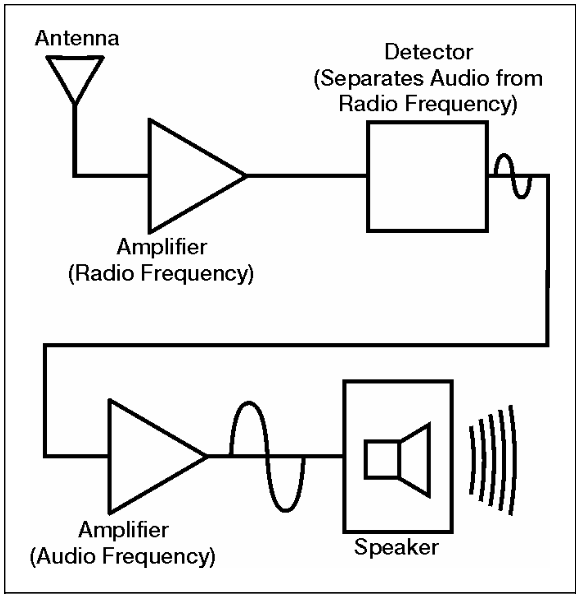


Figure 5-1. Amplifiers as Used in Radio Receiver

CLASSIFICATION OF AMPLIFIERS

5-8. Most electronic devices use at least one amplifier. However, there are many types of amplifiers. It would be impossible to try to describe all the different types of amplifiers. You will be shown the general principles of amplifiers and some typical amplifier circuits.

5-9. Most amplifiers can be classified in two ways. The first classification is by their function. This means they are basically voltage amplifiers or power amplifiers. The second

classification is by their frequency response; in other words, what frequencies they are designed to amplify.

5-10. If you describe an amplifier by these two classifications, you will have a good working description of the amplifier. You may not know what the exact circuitry is, but you will know what the amplifier does and the frequencies that it is designed to handle.

VOLTAGE AMPLIFIERS AND POWER AMPLIFIERS

5-11. All amplifiers are current-control devices. The input signal to an amplifier controls the current output of the amplifier. The connections of the amplifying device (such as the electron tube, transistor, magnetic amplifier, and so forth) and the circuitry of the amplifier determine the classification.

5-12. A voltage amplifier is an amplifier in which the output signal voltage is larger than the input signal voltage. In other words, a voltage amplifier amplifies the voltage of the input signal.

5-13. A power amplifier is an amplifier in which the output signal power is greater than the input signal power. In other words, a power amplifier amplifies the power of the input signal. Most power amplifiers are used as the final amplifier (stage of amplification) and control (or drive) the output device. The output device could be a speaker, an indicating device, an antenna, or the heads on a tape recorder. Whatever the device, the power to make it work (or drive it) comes from the final stage of amplification.

5-14. Figure 5-2 shows a simple block diagram of a voltage amplifier with its input and output signals and a power amplifier with its input and output signals. Notice that in view (A) the output signal voltage is larger than the input signal voltage. Since the current values for the input and output signals are not shown, you cannot tell if there is a power gain in addition to the voltage gain. In view (B), the output signal voltage is less than the input signal voltage. As a voltage amplifier, this circuit has a gain of less than 1. However, the output power is greater than the input power. Therefore, this circuit is a power amplifier.

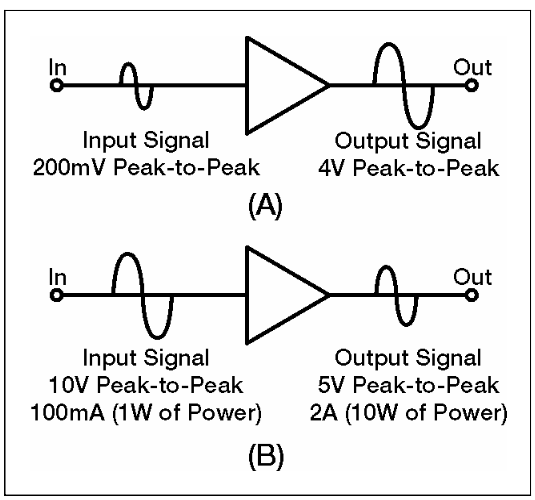


Figure 5-2. Block Diagram of Voltage and Power Amplifiers

5-15. The classification of an amplifier, as a voltage or power amplifier, is made by comparing the characteristics of the input and output signals. If the output signal is larger in voltage amplitude than the input signal, the amplifier is a voltage amplifier. If there is no

voltage gain, but the output power is greater than the input power, the amplifier is a power amplifier.

FREQUENCY RESPONSE OF AMPLIFIERS

5-16. In addition to being classified by function, amplifiers are classified by frequency response. You may wonder why the frequency response is important. The frequency response of an amplifier refers to the band of frequencies or frequency range that the amplifier was designed to amplify.

5-17. The reason an amplifier, designed to amplify a signal of 100 Hz, does not work as well at 1,000 MHz is because the components of the amplifier respond differently at different frequencies. The amplifying device (such as the electron tube, transistor, magnetic amplifier, and so forth) itself will have frequency limitations and respond in different ways as the frequency changes. Capacitors and inductors in the circuit will change their reactance as the frequency changes. Even the slightest amounts of capacitance and inductance between the circuit wiring and other components (interelectrode capacitance and self-inductance) can become significant at high frequencies. Since the response of components varies with the frequency, the components of an amplifier are selected to amplify a certain range or band of frequencies.

5-18. The three broad categories of frequency response for amplifiers are audio amplifier, RF amplifier, and video amplifier. An audio amplifier is designed to amplify frequencies between 15 Hz and 20 KHz. Amplifiers that are designed for this entire band of frequencies or any band of frequencies contained in the audio range is considered to be an audio amplifier. RF amplifiers are designed to amplify frequencies between 10 KHz and 100,000 MHz. A single amplifier will not amplify the entire RF range, but any amplifier whose frequency band is included in the RF range is considered an RF amplifier. A video amplifier is an amplifier designed to amplify a band of frequencies from 10 Hz to 6 MHz. Since this is such a wide band of frequencies, these amplifiers are sometimes called wide-band amplifiers. While a video amplifier will amplify a very wide band of frequencies, it does not have the gain of narrower-band amplifiers. It also requires many more components than a narrow-band amplifier to enable it to amplify a wide range of frequencies.

TRANSISTOR AMPLIFIERS

5-19. A transistor amplifier is a current-control device. The current in the base of the transistor (which is dependent on the emitter-base bias) controls the current in the collector. A vacuum-tube amplifier is also a current-control device. The grid bias controls the plate current.

5-20. You might hear that a vacuum tube is a voltage-operated device (since the grid does not need to draw current) while the transistor is a current-operated device. You might agree with this statement, but the vacuum tube and the transistor are still current-control devices. The whole secret to understanding amplifiers is to remember that fact. Once current is controlled you can use it to give you a voltage gain or a power gain.

5-21. This chapter will use transistor amplifiers to present the concepts and principles of amplifiers. These concepts apply to vacuum-tube amplifiers and, in most cases, magnetic amplifiers as well as transistor amplifiers.

AMPLIFIER CLASSES OF OPERATION

5-22. The class of operation of an amplifier is determined by the amount of time (in relation to the input signal) that current flows in the output circuit. This is a function of the operating point of the amplifying device. The operating point of the amplifying device is determined by the bias applied to the device. There are four classes of operation for an amplifier. These four classes are A, B, AB, and C. Each class of operation has certain uses and characteristics. No one class of operation is "better" than any other class. The selection of the "best" class of operation is determined by the use of the amplifying circuit.

Class A Operation

5-23. Figure 5-3 shows the class A operation of a simple transistor amplifier. Since the output signal is a 100 percent (or 360°) copy of the input signal, current in the output circuit must flow for 100 percent of the input signal time. This is the definition of a class A amplifier. Amplifier current flows for 100 percent of the input signal.

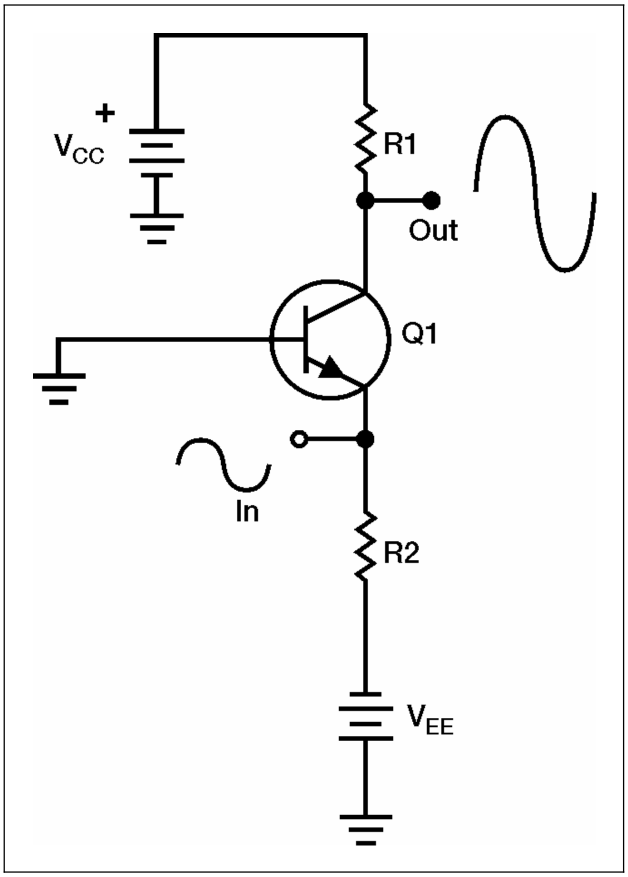


Figure 5-3. Simple Class A Transistor Amplifier

5-24. The class A amplifier has the characteristics of good fidelity and low efficiency. Fidelity means that the output signal is just like the input signal in all respects except amplitude. It has the same shape and frequency. In some cases, there may be a phase difference between the input and output signal (usually 180°), but the signals are still considered to be "good copies". The signal is said to be distorted if the output signal is not like the input signal in shape or frequency. Distortion is any undesired change in a signal from input to output.

5-25. The efficiency of an amplifier refers to the amount of power delivered to the output compared to the power supplied to the circuit. Since every device takes power to operate, if the amplifier operates for 360° of the input signal, it uses more power than if it only operates for 180° of the input signal. If the amplifier uses more power, less power is available for the output signal and efficiency is lower. Since class A amplifiers operate (have current flow) for 360° of the input signal, they are low in efficiency. This low efficiency is acceptable in class A amplifiers because they are used where efficiency is not as important as fidelity.

Class B Operation

5-26. A class B amplifier operates for 50 percent of the input signal. Figure 5-4 shows a simple class B amplifier. In the circuit, the base-emitter bias will not allow the transistor to conduct whenever the input signal becomes positive. Therefore, only the negative portion of the input signal is reproduced in the output signal. Even though only half the input signal is desired in the output, you would use a class B amplifier instead of a simple rectifier because the rectifier does not amplify. The output signal of a rectifier cannot be higher in amplitude than the input signal. The class B amplifier not only reproduces half the input signal, but amplifies it as well.

5-27. Class B amplifiers are twice as efficient as Class A amplifiers since the amplifying device conducts (and uses power) for half of the input signal. Where exactly 50 percent of the input signal must be amplified, a class B amplifier is used. If less than 50 percent of the input signal is needed, a class C amplifier is used.

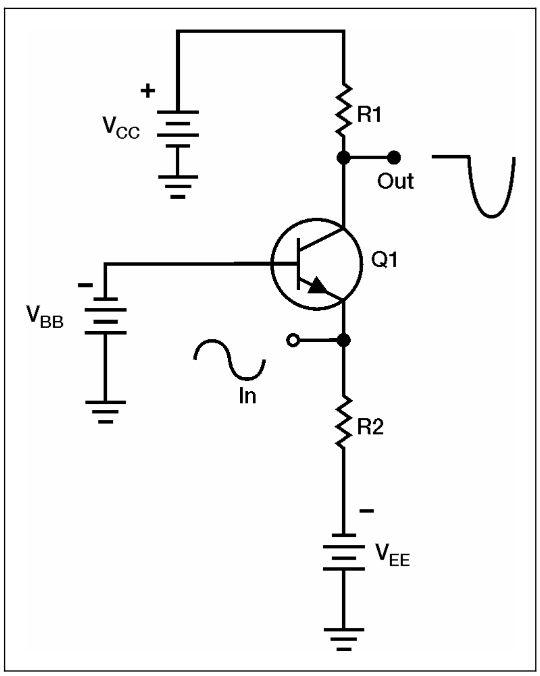


Figure 5-4. Simple Class B Transistor Amplifier

Class AB Operation

5-28. If the amplifying device is biased in such a way that current flows in the device for 51 to 99 percent of the input signal, the amplifier is operating class AB. Figure 5-5 shows a simple class AB amplifier.

5-29. Notice that the output signal is distorted. The output signal no longer has the same shape as the input signal. The portion of the output signal that appears to be cut off is caused by the lack of current through the transistor. When the emitter becomes positive enough, the transistor cannot conduct because the base-to-emitter junction is no longer forward biased. Any further increase in input signal will not cause an increase in output signal voltage.

5-30. Class AB amplifiers have better efficiency and poorer fidelity than class A amplifiers. They are used when the output signal need not be a complete reproduction of the input signal. However, both positive and negative portions of the input signal must be available at the output.

5-31. Class AB amplifiers are usually defined as amplifiers operating between class A and class B. This is because, class A amplifiers operate on 100 percent of input signal and class B amplifiers operate on 50 percent of the input signal. Any amplifier operating between these two limits is operating class AB.

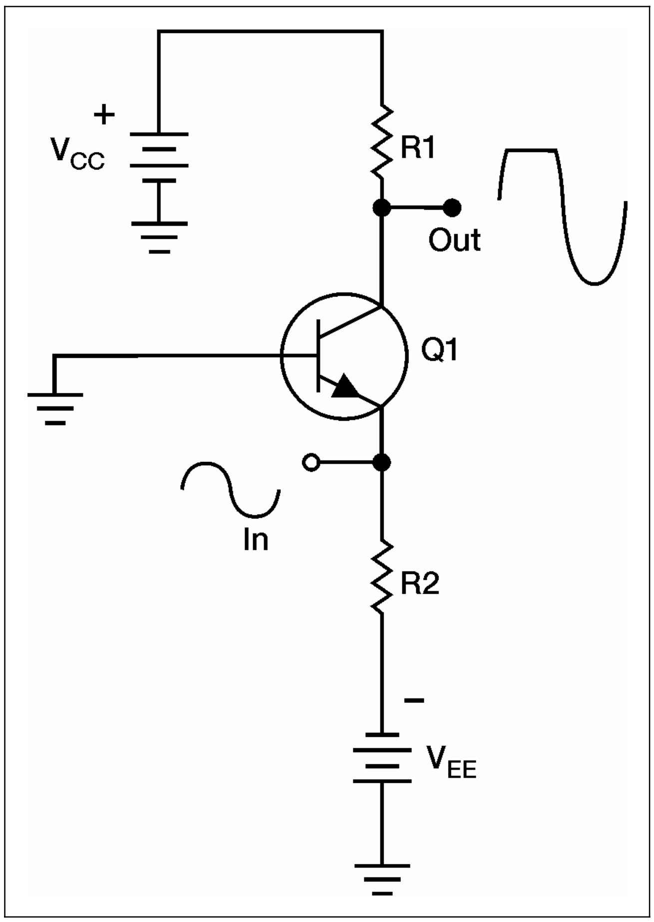


Figure 5-5. Simple Class AB Transistor Amplifier

Class C Operation

5-32. Figure 5-6 shows a simple class C amplifier. Notice that only a small portion of the input signal is present in the output signal. Since the transistor does not conduct except during small portions of the input signal, this is the most efficient amplifier. However, it

also has the worst fidelity. The output signal bears very little resemblance to the input signal.

5-33. Class C amplifiers are used where the output signal need only be present during part of one-half of the input signal. Any amplifier that operates on less than 50 percent of the input signal is operating class C.

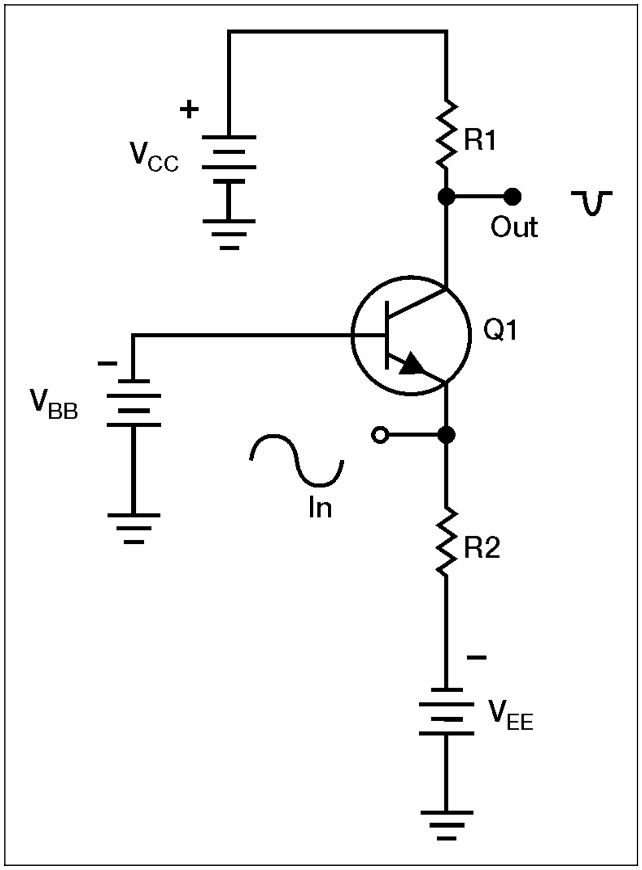


Figure 5-6. Simple Class C Transistor Amplifier

AMPLIFIER COUPLING

5-34. Remember, almost every electronic device contains at least one stage of amplification. Many devices contain several stages of amplification and therefore several amplifiers. Stages of amplification are added when a single stage will not provide the required amount of amplification. For example, if a single stage of amplification will provide a maximum gain of 100 and the desired gain from the device is 1,000, two stages of amplification will be required. The two stages might have gains of 10 and 100, 20 and 50, or 25 and 40. The overall gain is the product of the individual stages (10 x 100 = 20 x 50 = 25 x 40 = 1,000).

5-35. Figure 5-7 shows the effect of adding stages of amplification. As stages of amplification are added, the signal increases and the final output (from the speaker) is increased.

5-36. Whether an amplifier is one of a series in a device or a single stage connected between two other devices (top view, Figure 5-7), there must be some way for the signal to enter and leave the amplifier. The process of transferring energy between circuits is known

as coupling. There are various ways of coupling signals into and out of amplifier circuits. The following is a description of some of the more common methods of amplifier coupling.

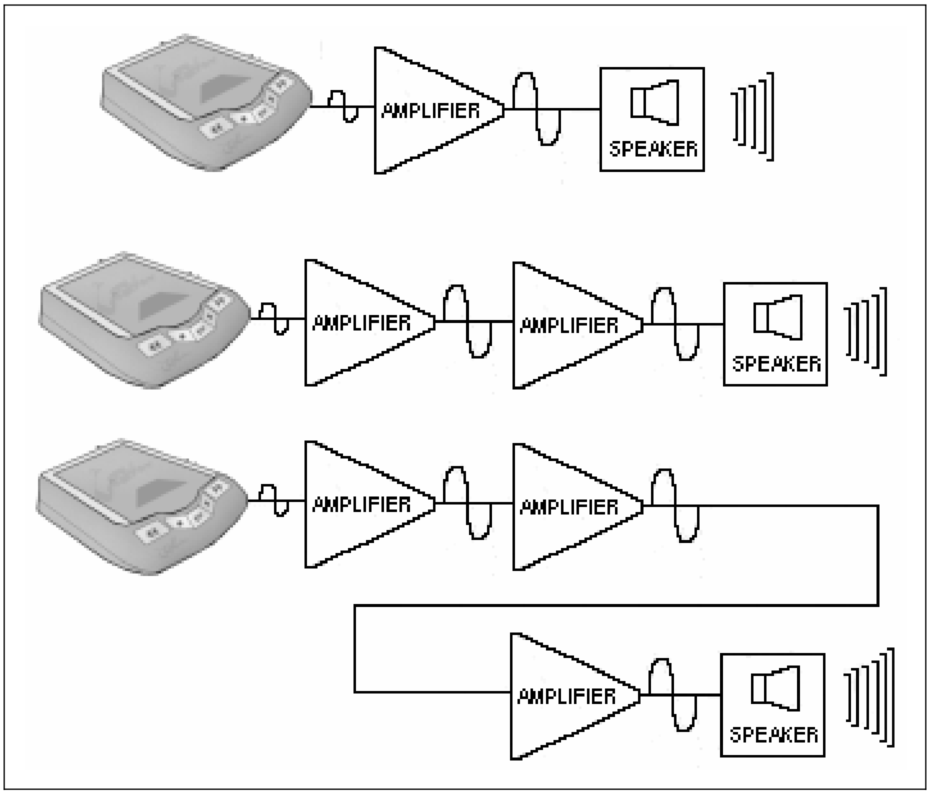


Figure 5-7. Adding Stages of Amplification

Direct Coupling

5-37. This method uses the least number of circuit elements. Therefore, it is perhaps the easiest to understand. In direct coupling the output of one stage is connected directly to the input of the following stage. Figure 5-8 shows two direct-coupled transistor amplifiers.

5-38. Notice that the output (collector) of Q1 is connected directly to the input (base) of Q2. The network of R4, R5, and R6 is a voltage divider used to provide the bias and operating voltages for Q1 and Q2. The entire circuit provides two stages of amplification.

5-39. Direct coupling provides a good frequency response since no frequency-sensitive components (inductors and capacitors) are used. The frequency response of a circuit using direct coupling is affected only by the amplifying device itself.

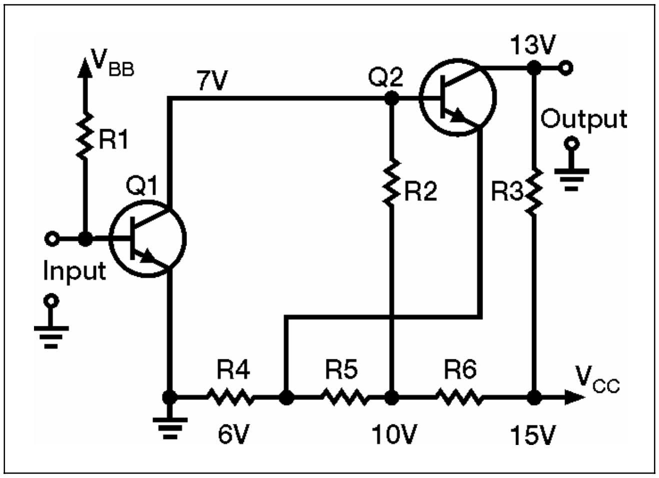


Figure 5-8. Direct-coupled Transistor Amplifier

5-40. Direct coupling has several disadvantages. The major problem is the power supply requirements for direct-coupling amplifiers. Each succeeding stage requires higher voltage. The load and voltage divider resistors use a large amount of power and the biasing can become very complicated. It is also difficult to match the impedance from stage to stage with direct coupling. Impedance matching is covered a little later in this chapter. The direct-coupled amplifier is also not very efficient and the losses increase as the number of stages increase. Because of the disadvantages, direct coupling is not used very often.

RC Coupling

5-41. The most commonly used coupling in amplifiers is RC coupling. Figure 5-9 shows an RC-coupling network. The network of R1, R2, and C1 enclosed in the dashed lines of the figure is the coupling network. You may notice that the circuitry for Q1 and Q2 is incomplete. That is intentional so that you can concentrate on the coupling network.

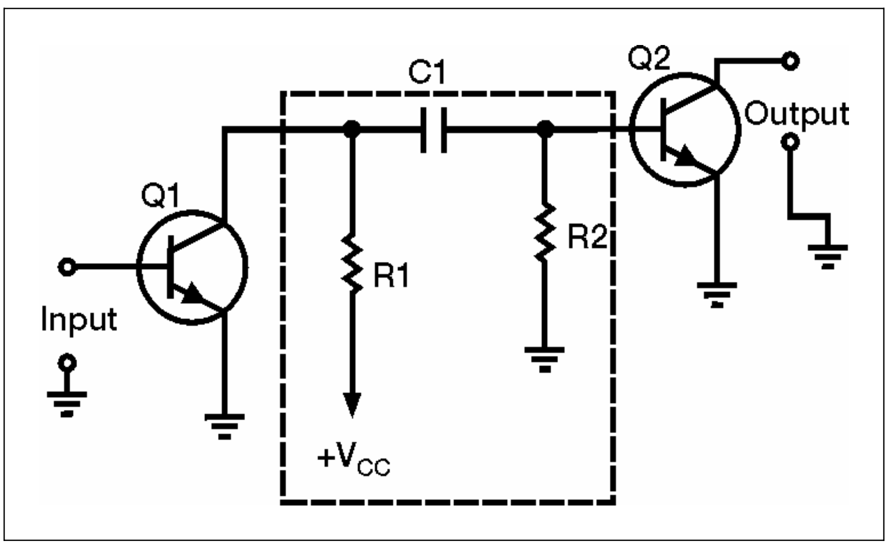


Figure 5-9. RC-coupled Transistor Amplifier

5-42. R1 acts as a load resistor for Q1 (the first stage) and develops the output signal of that stage. We already discussed how a capacitor reacts to AC and DC. The capacitor (C1) "blocks " the DC of Q1's collector, but "passes" the AC output signal. R2 develops this passed, or coupled, signal as the input signal to Q2 (the second stage), This arrangement allows the coupling of the signal while it isolates the biasing of each stage. This solves many of the problems associated with direct coupling.

5-43. RC coupling does have a few disadvantages. The resistors use DC power and so the amplifier has low efficiency. The capacitor tends to limit the low-frequency response of the amplifier and the amplifying device itself limits the high-frequency response. This is usually not a problem for audio amplifiers. Techniques for overcoming these frequency limitations will be covered later in this chapter.

5-44. Before moving on to the next type of coupling, the capacitor in the RC coupling should be considered. Remember, that capacitive reactance (X_C) is determined by the following formula:

$$X_C = \frac{1}{2\pi fC}$$

This explains why the low frequencies are limited by the capacitor. As frequency decreases, X_C increases. This causes more of the signal to be "lost " in the capacitor.

5-45. The formula for X_C also shows that the value of capacitance (C) should be relatively high so that capacitive reactance (X_C) can be kept as low as possible. So, when a capacitor is used as a coupling element, the capacitance should be relatively high so that it will couple the entire signal well and not reduce or distort the signal.

Impedance Coupling

5-46. Impedance coupling is very similar to RC coupling. The difference is the use of an impedance device (a coil) to replace the load resistor of the first stage.

5-47. Figure 5-10 shows an impedance-coupling network between two stages of amplification. L1 is the load for Q1 and develops the output signal of the first stage. Since the DC resistance of a coil is low, the efficiency of the amplifier stage is increased. The amount of signal developed in the output of the stage depends on the inductive reactance of L1. Remember the formula for inductive reactance is $X_L = 2\pi fL$.

5-48. The formula shows that for inductive reactance to be large, either inductance or frequency or both must be high. Therefore, load inductors should have relatively large amounts of inductance and are most effective at high frequencies. This explains why impedance coupling is usually not used for audio amplifiers.

5-49. The rest of the coupling network (C1 and R1) functions just as their counterparts (C1 and R2) in the RC-coupling network. C1 couples the signal between stages while blocking the DC and R1 develops the input signal to the second stage (Q2).

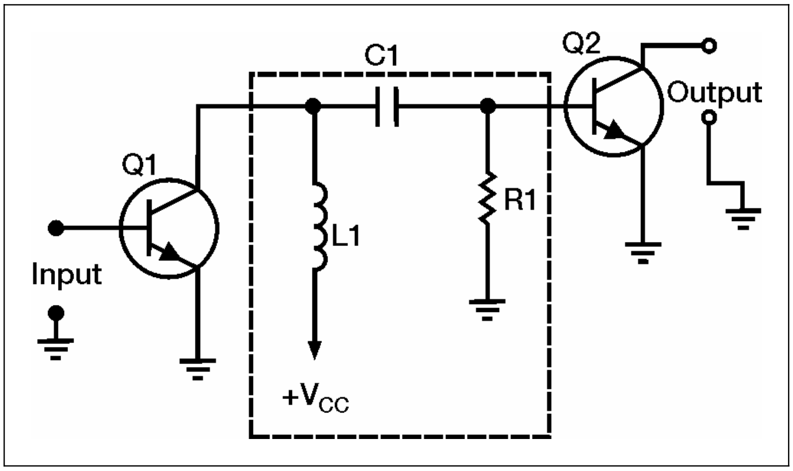


Figure 5-10. Impedance-coupled Transistor Amplifier

Transformer Coupling

5-50. Figure 5-11 shows a transformer-coupling network between two stages of amplification. The transformer action of T1 couples the signal from the first stage to the second stage. The primary of T1 acts as the load for the first stage (Q1) and the secondary of T1 acts the developing impedance for the second stage (Q2). No capacitor is needed because transformer action couples the signal between the primary and secondary of T1.

5-51. The inductors that make up the primary and secondary of the transformer have very little DC resistance, so the efficiency of the amplifiers very high. Transformer coupling is very often used for the final output (between the final amplifier stage and the output device) because of the impedance-matching qualities of the transformer. The frequency response transformer-coupled amplifiers are limited by the inductive reactance of the transformer just as it was limited in impedance coupling.

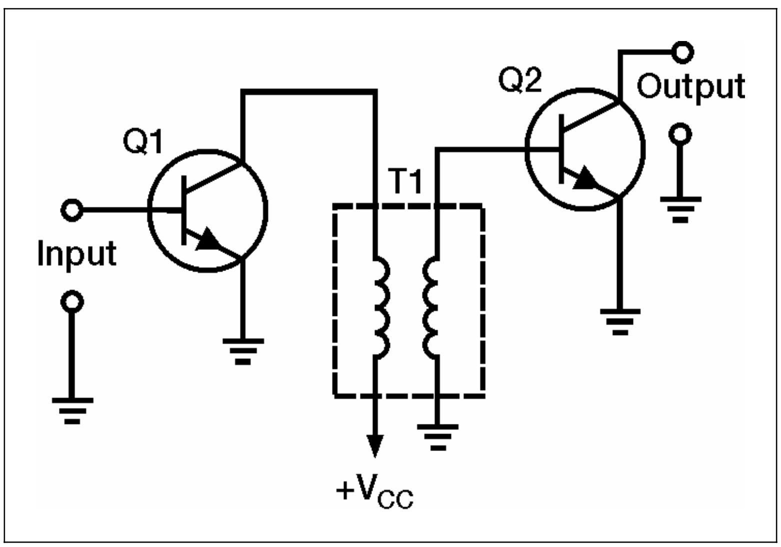


Figure 5-11. Transformer-coupled Transistor Amplifier

IMPEDANCE CONSIDERATIONS FOR AMPLIFIERS

5-52. Remember that efficiency and impedance are important in amplifiers. have been shown that any amplifier is a current-control device. Now there are two other principles you need to know. The first principle is that there is no such thing as “something for nothing” in electronics. That means that every time you do something to a signal it costs something. It might mean a loss in fidelity to get high power. Some other compromise might also be made when a circuit is designed. Regardless of the compromise, every stage will require and use power. The second principle is “do things as efficiently as possible”. The improvement and design of electronic circuits is an attempt to do things as cheaply as possible, in terms of power, when all the other requirements (fidelity, power output, frequency range, and so forth) have been met.

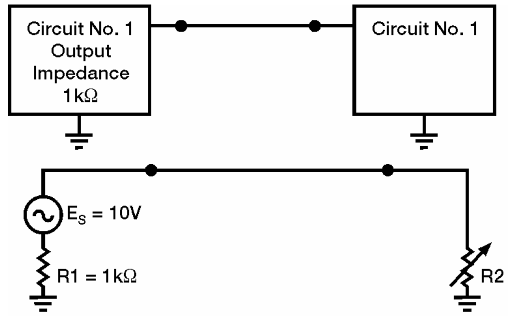
5-53. The most efficient device is the one that does the job with the least loss of power. One of the largest losses of power is caused by impedance differences between the output of one circuit and the input of the next circuit. Perhaps the best way to think of an impedance difference (mismatch) between circuits is to think of different-sized water pipes. If you try to connect a one-inch water pipe to a two-inch water pipe without an adapter you will lose water. An impedance-matching device is like that adapter. It allows the connection of two devices with different impedances without the loss of power.

5-54. Figure 5-12 shows two circuits connected together. Circuit number 1 can be considered as an AC source (E_S) whose output impedance is represented by a resistor (R1). It can be considered as an AC source because the output signal is an AC voltage and comes from circuit number 1 through the output impedance. A resistor in series with the source represents the input impedance of circuit number 2. The resistance is shown as variable to show what will happen as the input impedance of circuit number 2 is changed. The chart below the circuit shows the effect of a change in the input impedance of circuit number 2 (R2) on current (I), signal voltage developed at the input of circuit number 2 (E_{R2}), the power at the output of circuit number 1 (P_{R1}), and the power at the input to circuit number 2 (P_{R2}).

5-55. Two other important facts are shown in this chart. First, the power at the input to circuit number 2 is greatest when the impedances are equal (matched). The power is also equal at the output of circuit number 1 and the input of circuit number 2 when the impedance is matched. Second, the largest voltage signal is developed at the input to circuit number 2 when its input impedance is much larger than the output impedance of circuit number 1. However, the power at the input of circuit number 2 is very low under these conditions. So you must decide what conditions you want in coupling two circuits together and select the components appropriately.

5-56. Two important points to remember about impedance matching are as follows:

- Maximum power transfer requires matched impedance.
- To get maximum voltage at the input of a circuit requires an intentional impedance mismatch with the circuit that is providing the input signal.



R2	I	E_{R2}	P_{R1}	P_{R2}
100Ω	9mA	900mV	82.6mW	8.3mW
200Ω	8.3mA	1.67V	69.4mW	13.9mW
500Ω	6.7mA	3.33V	44.4mW	22.2mW
1kΩ	5mA	5V	25mW	25mW
2kΩ	3.3mA	6.67V	11.1mW	22.2mW
5kΩ	1.7mA	8.33V	2.7mW	13.9mW
10kΩ	.9mA	9.09V	.9mW	8.3mW

Figure 5-12. Effect of Impedance Matching in the Coupling of Two Circuits

IMPEDANCE CHARACTERISTICS OF AMPLIFIER CONFIGURATIONS

5-57. You have seen the importance of impedance matching the stages in an electronic device. Next, we will look at the impedance characteristics of an amplifier. The input and output impedances of a transistor amplifier depend upon the configuration of the transistor. You have already been introduced to the CE, CB, and CC transistor configurations. Figure 5-13 shows examples of these configurations and their impedance characteristics.

> NOTE: Only approximate impedance values are shown. This is because the exact impedance values will vary from circuit to circuit. The impedance of any particular circuit depends upon the device (transistor) and the other circuit components. The value of impedance can be computed by dividing the signal voltage by the signal current.

5-58. The CE configuration provides medium input impedance and medium output impedance. The CB configuration provides low input impedance and high output impedance. The CC configuration provides high input impedance and low output impedance. The CC configuration is often used to provide impedance matching between high output impedance and low input impedance.

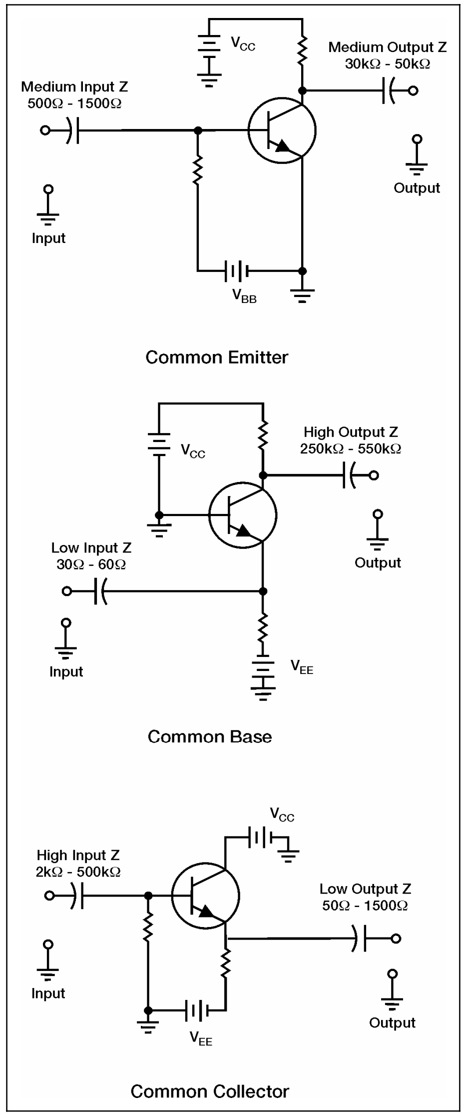


Figure 5-13. Transistor Amplifier Configuration and Their Impedance Characteristics

5-59. If the amplifier stage is transformer coupled, the turns ratio of the transformer can be selected to provide impedance matching. The relationship is expressed in the following formula:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$$

Where:

N_P= number of turns in the primary

N_S= number of turns in the secondary

Z_P= impedance of the primary

Z_S= impedance of the secondary

As you can see, impedance matching between stages can be accomplished by a combination of the amplifier configuration and the components used in the amplifier circuit.

AMPLIFIER FEEDBACK

5-60. Turning down the volume of a public address system, when a squeal or high-pitched noise comes from the speaker, will cause the noise to stop. That noise was an indication that the amplifier (at least one stage of amplification) had begun oscillating. All you need to know for now is that oscillation is caused by a small part of the signal from the amplifier output being sent back to the input of the amplifier. The signal is amplified and again sent back to the input where it is amplified again. This process continues and the result is a loud noise out of the speaker. The process of sending part of the output signal of an amplifier back to the input of the amplifier is called feedback.

5-61. The two types of feedback in amplifiers are called POSITIVE FEEDBACK (also called regenerative feedback) and NEGATIVE FEEDBACK (also called degenerative feedback). The difference between these two types is whether the feedback signal is "in phase" or "out of phase" with the input signal.

5-62. Positive feedback occurs when the feedback signal is in phase with the input signal. Figure 5-14 shows a block diagram of an amplifier with positive feedback. Notice that the feedback signal is in phase with the input signal. This means that the feedback signal will add to or "regenerate" the input signal. The result is a larger amplitude output signal than would occur without the feedback. This type of feedback is what causes the public address system to squeal as described above.

5-63. Figure 5-15 is a block diagram of an amplifier with negative feedback. In this case the feedback signal is out of phase with the input signal. This means that the feedback sign will subtract from or "degenerate" the input signal. This results in a lower amplitude output signal than would occur without the feedback.

5-64. Sometimes feedback that is not desired occurs in an amplifier. This happens at high frequencies and limits the high-frequency response of an amplifier. Unwanted feedback also occurs as the result of some circuit components used in the biasing or coupling network. The usual solution to unwanted feedback is a feedback network of the opposite type. For example, a positive feedback network would counteract unwanted negative feedback.

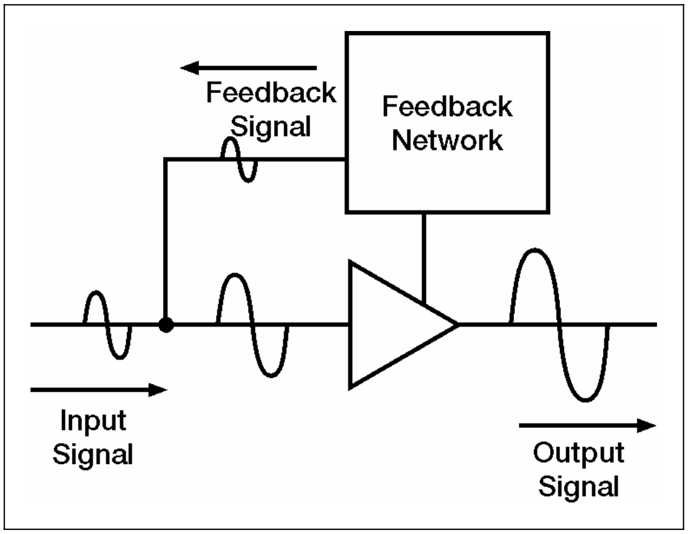


Figure 5-14. Positive Feedback in an Amplifier

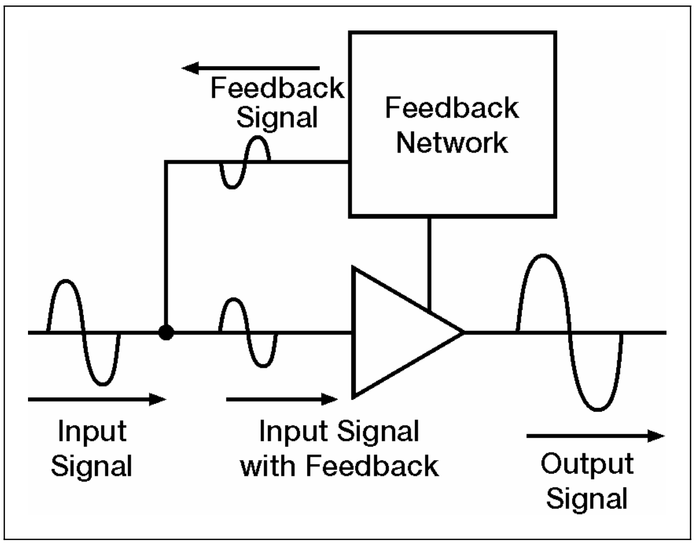


Figure 5-15. Negative Feedback in an Amplifier

5-65. Feedback is also used to get the ideal input signal. Normally, the maximum output signal is desired from an amplifier. The amount of the output signal from an amplifier is dependent on the amount of the input signal. However, if the input signal is too large, the amplifying device will be saturated and/or cut off during part of the input signal. This causes the output signal to be distorted and reduces the fidelity of the amplifier. Amplifiers must provide the proper balance of gain and fidelity.

5-66. Figure 5-16 shows the way in which feedback can be used to provide the maximum output signal without a loss in fidelity. In view (A), an amplifier has good fidelity, but less gain than it could have. By adding some positive feedback (view (B)), the gain of the stage is increased. In view (C), an amplifier has so much gain and such a large input signal that the output signal is distorted. This distortion is caused by the amplifying device becoming saturated and cutoff. By adding a negative feedback system (view (D)), the gain of the stage is decreased and the fidelity of the output signal improved.

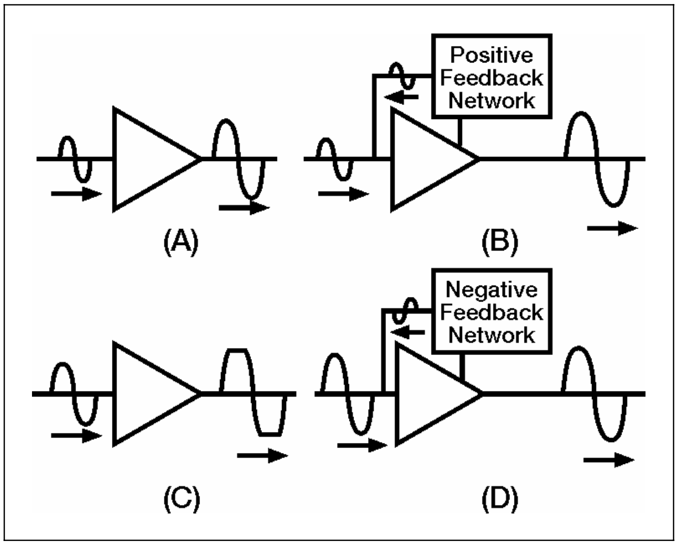


Figure 5-16. Feedback Uses in Amplifiers

5-67. Depending on the reasons requiring the feedback, positive and negative feedback are accomplished in many ways. The following are a few of the effects and methods of accomplishing feedback.

Positive Feedback

5-68. Remember, positive feedback is accomplished by adding part of the output signal in phase with the input signal. In a CB transistor amplifier, it is fairly simple to provide positive feedback. Since the input and output signals are in phase, you need only couple part of the output signal back to the input (see Figure 5-17).

5-69. The feedback network in this amplifier is made up of R2 and C2. The value of C2 should be large so that the capacitive reactance (X_C) will be low and the capacitor will couple the signal easily (this is also the case with the input and output coupling capacitors C1 and C3). The resistive value of R2 should be large to limit the amount of feedback signal and to ensure that the majority of the output signal goes on to the next stage through C3.

5-70. A more common configuration for transistor amplifiers is the CE configuration. Positive feedback is a little more difficult with this configuration because the input and output signals are 180° out of phase. Positive feedback can be accomplished by feeding a portion of the output signal of the second stage back to the input of the first stage (see Figure 5-18).

5-71. Figure 5-18 shows that each stage of amplification has a 180° phase shift. This means that the output signal of Q2 will be in phase with the input signal to Q1. A portion of the output signal of Q2 is coupled back to the input of Q1 through the feedback network of C3 and R3. R3 should have a large resistance to limit the amount of signal through the feedback network. C3 should have a large capacitance so the capacitive reactance is low and the capacitor will couple the signal easily.

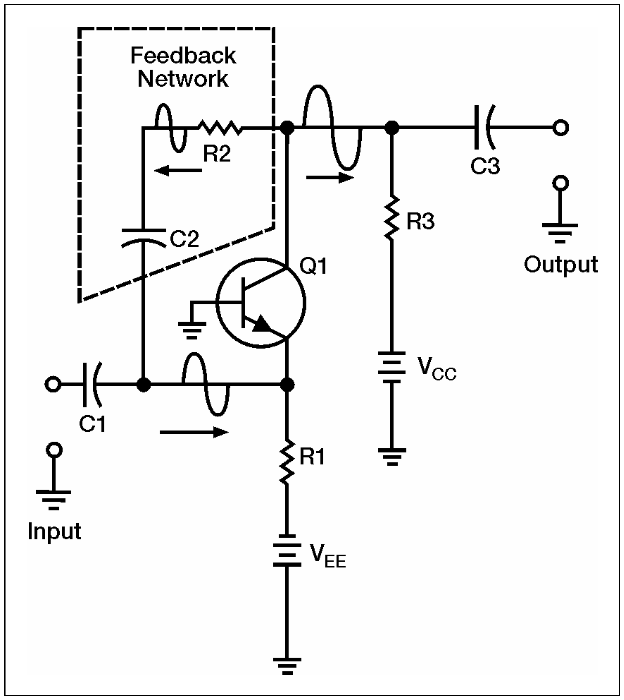


Figure 5-17. Positive Feedback in a Transistor Amplifier

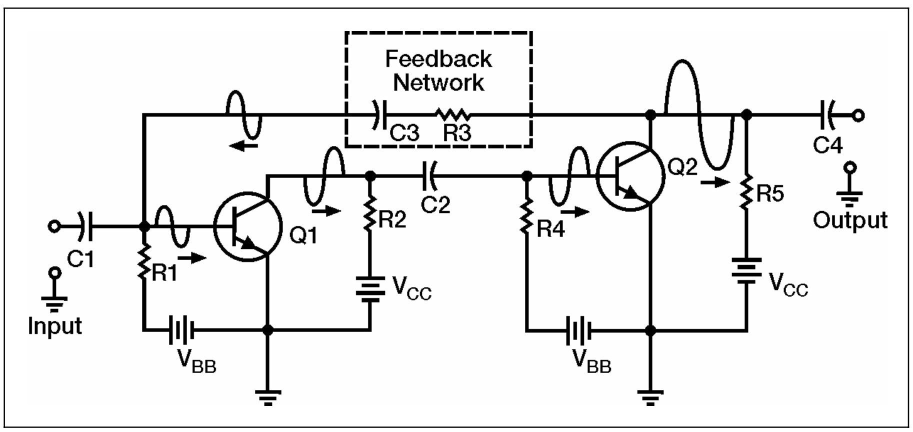


Figure 5-18. Positive Feedback in Two Stages of Transistor Amplification

5-72. Sometimes positive feedback is used to eliminate the effects of negative feedback that are caused by circuit components. Figure 5-19 shows one way in which a circuit component can cause negative feedback.

5-73. Figure 5-19, view (A) shows a CE transistor amplifier. An emitter resistor (R2) has been placed in this circuit to provide proper biasing and temperature stability. An undesired effect of this resistor is the development of a signal at the emitter in phase with the input signal on the base. This signal is caused by the changing current through the emitter resistor (R2) as the current through the transistor changes. You might think that this signal on the emitter is a form of positive feedback since it is in phase with the input signal; however, the emitter signal is really negative feedback. Current through the transistor is controlled by the base-to-emitter bias. If both the base and emitter become more positive by the same amount at the same time, current will not increase. It is the

difference between the base and emitter voltages that controls the current flow through the transistor.

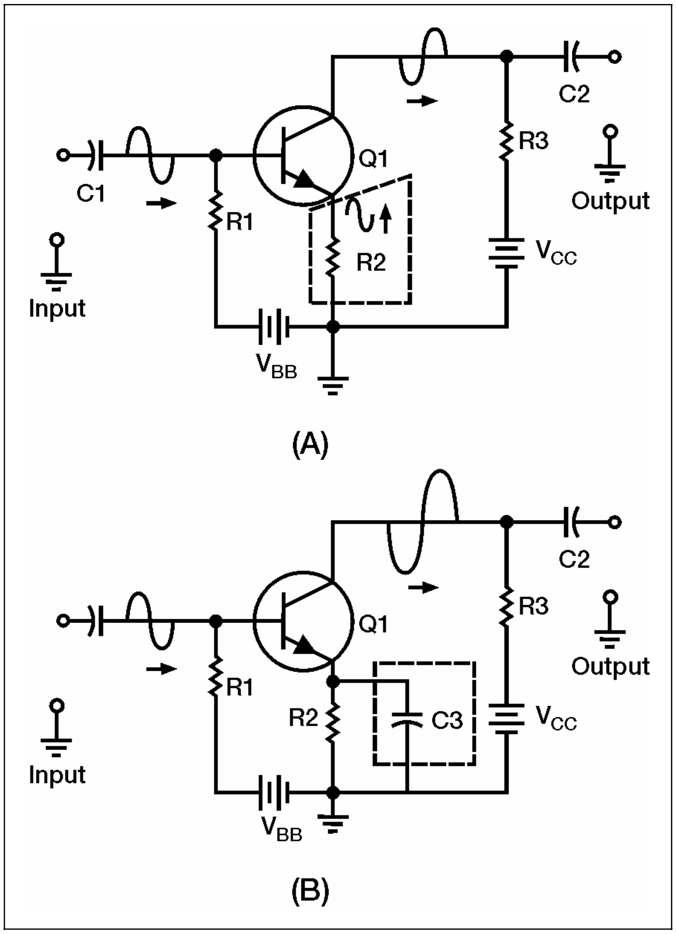


Figure 5-19. Decoupling (Bypass) Capacitor in a Transistor Amplifier

5-74. To stop negative feedback caused by the emitter resistor, you must find some way to remove the signal from the emitter. If the signal could be coupled to ground (decoupled) the emitter of the transistor would be unaffected. That is exactly what is done. A decoupling capacitor (C3 in view B) is placed between the emitter of Q1 and ground (across the emitter resistor). This capacitor should have a high capacitance so that it will pass the signal to ground easily. The decoupling capacitor (C3) should have the same qualities as the coupling capacitors (C1 and C2) of the circuit. Decoupling capacitors are also called bypass capacitors. Regardless of the method used to provide positive feedback in a circuit, the purpose is to increase the output signal amplitude.

Negative Feedback

5-75. Negative feedback is accomplished by adding part of the output signal out of phase with the input signal. You have seen that an emitter resistor in a CE transistor amplifier will develop a negative feedback signal. Other methods of providing negative feedback are similar to those methods used to provide positive feedback. The phase relationship of the feedback signal and the input signal is the only difference.

5-76. Figure 5-20 shows negative feedback in a CE transistor amplifier. The feedback network of C2 and R2 couples part of the output signal of Q1 back to the input. Since the output signal is 180° out of phase with the input signal, this causes negative feedback.

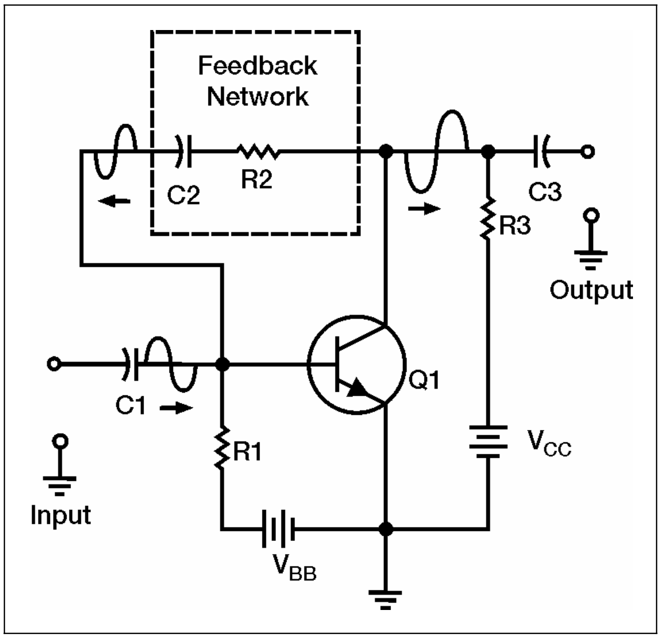


Figure 5-20. Negative Feedback in a Transistor Amplifier

5-77. Negative feedback is used to improve fidelity of an amplifier by limiting the input signal. Negative feedback can also be used to increase the frequency response of an amplifier. The gain of an amplifier decreases when the limit of its frequency response is reached. When negative feedback is used, the feedback signal decreases as the output signal decreases. At the limits of frequency response of the amplifier, the smaller feedback signal means that the effective gain (gain with feedback) is increased. This will improve the frequency response of the amplifier.

AUDIO AMPLIFIERS

5-78. An audio amplifier has been described as an amplifier with a frequency response from 15 Hz to 20 KHz. The frequency response of an amplifier can be shown graphically with a frequency-response curve. Figure 5-21 is the ideal frequency-response curve for an audio amplifier. This curve is practically “flat” from 15 Hz to 20 KHz. This means that the gain of the amplifier is equal between 15 Hz and 20 KHz. Above 20 KHz or below 15 Hz the gain decreases or “drops off” quite rapidly. The frequency response of an amplifier is determined by the components in the circuit.

5-79. The difference between an audio amplifier and other amplifiers is the frequency response of the amplifier. There are certain techniques and components used to change and extend the frequency response of an amplifier. The transistor itself will respond quite well to the audio frequency range. No special components are needed to extend or modify the frequency response.

5-80. You have seen the purpose of all the components in a transistor audio amplifier. We will not look at schematic diagrams of several audio amplifiers and the functions of each of the components will be discussed.

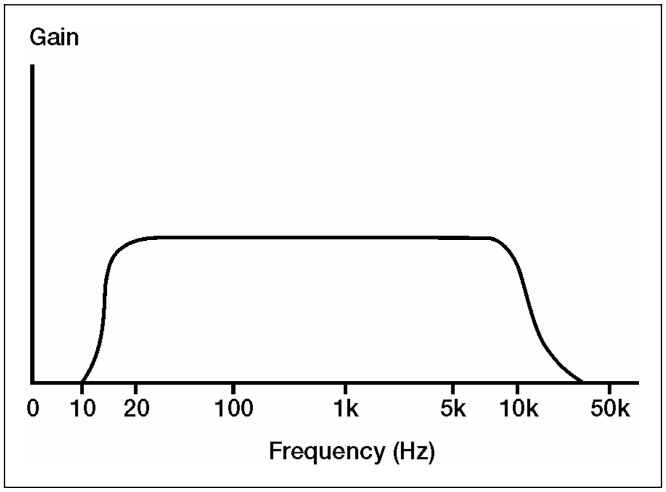


Figure 5-21. Ideal Frequency-response Curve for an Audio Amplifier

SINGLE-STAGE AUDIO AMPLIFIERS

5-81. Figure 5-22 shows the first single-stage audio amplifier. This circuit is a class A, CE, RC-coupled, transistor, audio amplifier. C1 is a coupling capacitor that couples the input signal to the base of Q1. R1 is used to develop the input signal and provide bias for the base of Q1. R2 is used to bias the emitter and provide temperature stability for Q1. C2 is used to provide decoupling (positive feedback) of the signal that would be developed by R2. R3 is the collector load for Q1 and develops the output signal. C3 is a coupling capacitor that couples the output signal to the next stage. V_{CC} represents the collector-supply voltage. Since the transistor is a CE configuration, it provides voltage amplification. The input and output signals are 180º out of phase. The input and output impedance are both medium. There is nothing new presented in this circuit. You should understand all of the functions of the components in this circuit. If you do not, look back at the various sections presented earlier in this chapter.

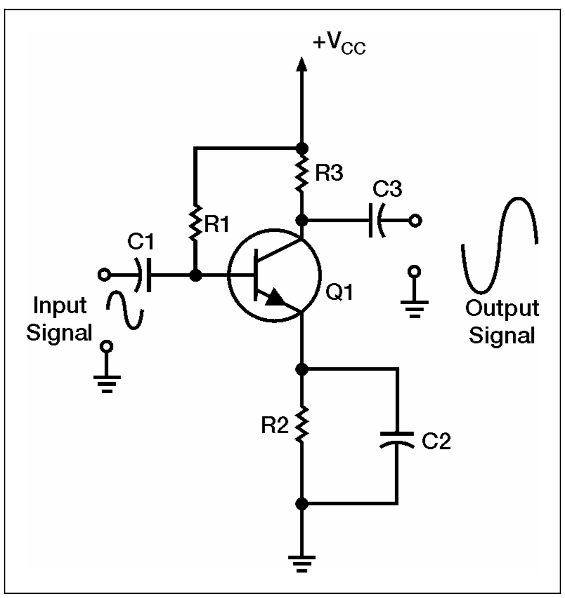


Figure 5-22. Class A, CE, RC-coupled, Transistor, Audio Amplifier

5-82. Figure 5-23 shows the second single-stage audio amplifier. This circuit is a class A, common-source, RC-coupled, FET, audio amplifier. C1 is a coupling capacitor, which couples the input signal to the gate of Q1. R1 is used to develop the input signal for the gate of Q1. R2 is used to bias the source of Q1. C2 is used to decouple the signal developed by R2 and to keep it from affecting the source of Q1. R3 is the drain load for Q1 and develops the output signal. C3 couples the output signal to the next stage. V_{DD} is the supply voltage for the drain of Q1. Since this is a common-source configuration, the input and output signals are 180° out of phase.

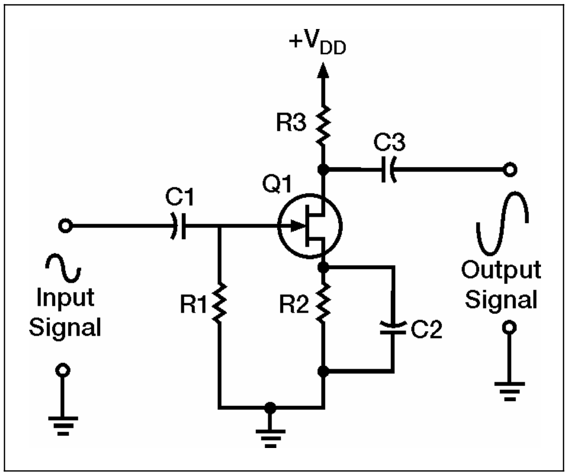


Figure 5-23. Class A, Common-source, RC-coupled, FET, Audio Amplifier

5-83. Figure 5-24 shows the third single-stage audio amplifier. This is a class A, CE, transformer-coupled, transistor, audio amplifier. The output device (speaker) is shown connected to the secondary winding of the transformer. C1 is a coupling capacitor, which couple the input signal to the base of Q1. R1 develops the input signal. R2 is used to bias the emitter of Q1 and provides temperature stability. C2 is a decoupling capacitor for R2. R3 is used to bias the base of Q1. The primary of T1 is the collector load for Q1 and develops the output signal. T1 couples the output signal to the speaker and provides impedance matching between the output impedance of the transistor (medium) and the impedance of the speaker (low).

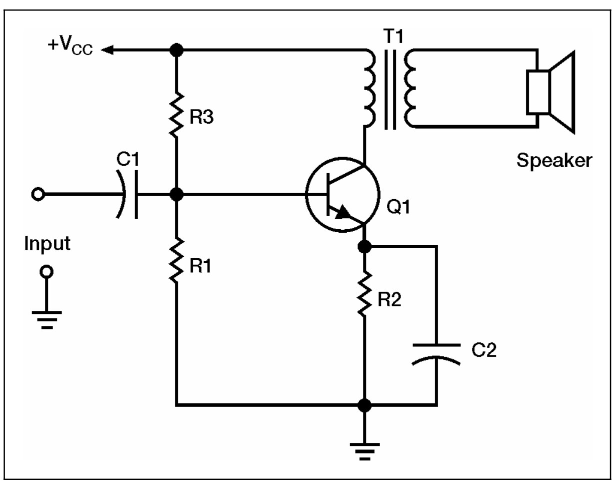


Figure 5-24. Class A, CE, Transformer-coupled, Transistor, Audio Amplifier

PHASE SPLITTERS

5-84. Sometimes it is necessary to provide two signals that are equal in amplitude but 180° out of phase with each other. The two signals can be provided from a single-input signal by the use of a phase splitter. A phase splitter is a device that produces two signals that differ in phase from each other from a single-input signal. Figure 5-25 is a block diagram of a phase splitter.

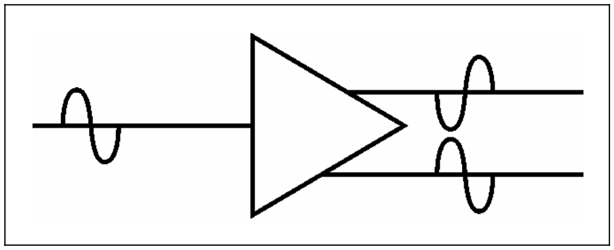


Figure 5-25. Block Diagram of a Phase Splitter

5-85. One way in which a phase splitter can be made is to use a center-tapped transformer. Remember, when the transformer secondary winding is center-tapped, two equal amplitude signals are produced. These signals will be 180° out of phase with each other. So a transformer with a center-tapped secondary fulfills the definition of a phase splitter. A transistor amplifier can also be configured to act as a phase splitter. Figure 5-26 shows one method on how this is done.

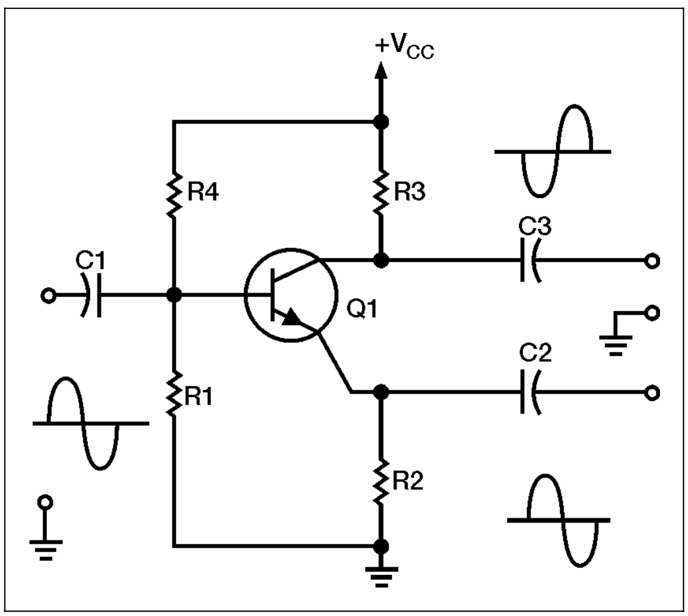


Figure 5-26. Single-stage Transistor Phase Splitter

5-86. C1 is the input signal coupling capacitor and couples the input signal to the base of Q1. R1 develops the input signal. R2 and R3 develop the output signals. R2 and R3 are equal resistances to provide equal amplitude output signals. C2 and C3 couple the output signals to the next stage. R4 is used to provide proper bias for the base of Q1.

5-87. This phase splitter is actually a single transistor combining the qualities of the CE and common-col1ector configurations. The output signals will be lower in amplitude than

the input signal, although they will be equal to each other in amplitude. If the output signals must be larger in amplitude than the input signal, use a circuit such as the one shown in Figure 5-27.

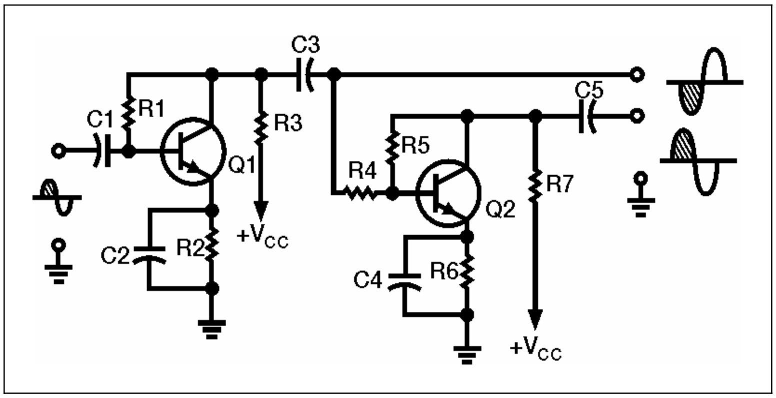


Figure 5-27. Two-stage Transistor Phase Splitter

5-88. Figure 5-27 also shows a two-stage phase splitter. C1 couples the input signal to the base of Q1. R1 develops the input signal and provides bias for the base of Q1. R2 provides bias and temperature stability for Q1. C2 decouples signals from the emitter of Q1. R3 develops the output signal of Q1. Since Q1 is configured as a CE amplifier, the output signal of Q1 is 180° out of phase with the input signal and larger in amplitude. C3 couples this output signal to the next stage through R4. R4 allows only a small portion of this output signal to be applied to the base of Q2. R5 develops the input signal and provides bias for the base of Q2. R6 is used for bias and temperature stability for Q2. C4 decouples signals from the emitter of Q2. R7 develops the output signal from Q2. Q2 is configured as a CE amplifier, so the output signal is 180° out of phase with the input signal to Q2 (output signal from Q1). The input signal to Q2 is 180° out of phase with the original input signal, so the output from Q2 is in phase with the original input signal. C5 couples this output signal to the next stage. So the circuitry shown provides two output signals that are 180° out of phase with each other. The output signals are equal in amplitude with each other but larger than the input signal.

PUSH-PULL AMPLIFIERS

5-89. One use of phase splitters is to provide input signals to a single-stage amplifier that uses two transistors. These transistors are configured so that the output signals will add together. This allows more gain (usually power gain) than one transistor could supply by itself. This circuit is usually used as a power amplifier and is known as a push-pull amplifier.

5-90. Figure 5-28 shows the circuit of a transistor push-pull amplifier. The phase splitter for this amplifier is the transformer T1. However, any one of the phase splitters shown earlier in the chapter could be used.

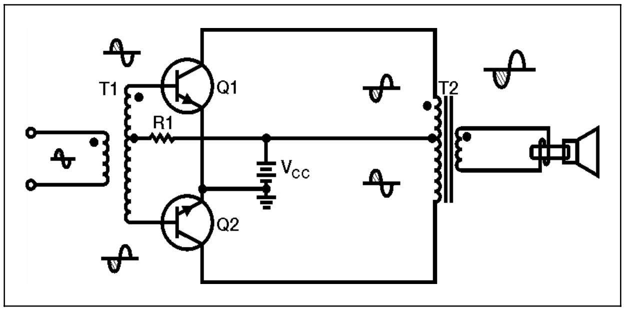


Figure 5-28. Class A Transistor Push-Pull Amplifier

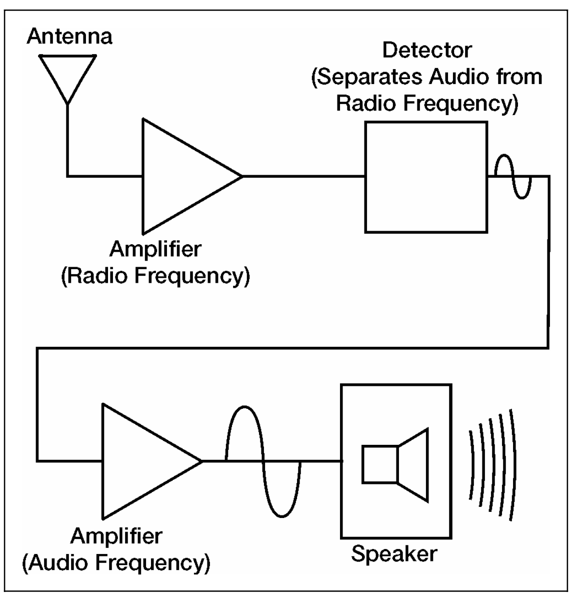
5-91. R1 provides the proper bias for Q1 and Q2. The tapped secondary of T1 develops the two input signals for the bases of Q1 and Q2. The tapped primary of T2 develops the output signals of Q1 and Q2. T2 couples the output signal (combined) to the speaker and provides impedance matching.

5-92. The circuit shown is a class A amplifier. However, because the push-pull amplifier produces two outputs (from the transistors) 180° out of phase with each other, class B operation could be used. Half of the original input signal would be amplified by Q1and the other half by Q2. In this way, the entire output signal would be present at the speaker. Class B operation is more efficient than class A operation and the gain of the push-pull amplifier would be more than a single transistor could provide.

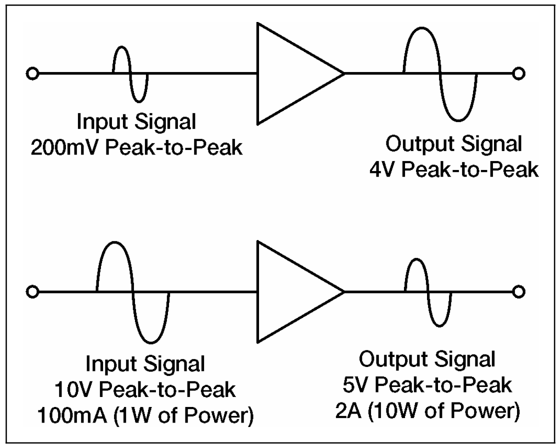
SUMMARY

5-93. Now that we have completed this chapter, the following is a short review of the more important points. Answer the check-on-learning questions, found after the summary, to determine how much you have learned from this chapter.

AMPLIFIER - a device that enables an input signal to control an output signal. The output signal will have some (or all) of the characteristics of the input signal but will generally be larger than the input signal in terms of voltage, current, or power.

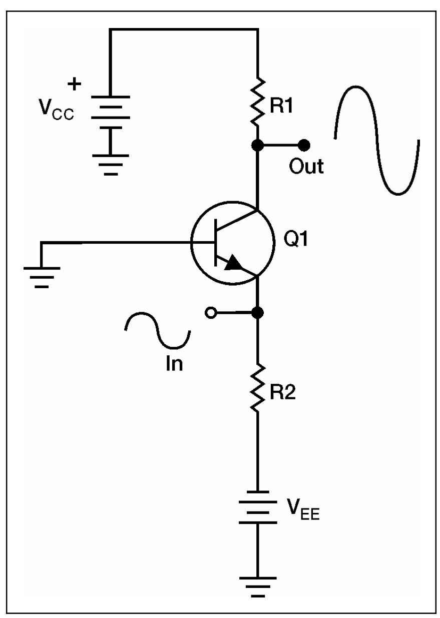


VOLTAGE AMPLIFIER **-** amplifiers are classified by FUNCTION and FREQUENCY RESPONSE. Function refers to an amplifier being a VOLTAGE AMPLIFIER or a POWER AMPLIFIER. Voltage amplifiers provide voltage amplification and power amplifiers provide power amplification. The frequency response of an amplifier can be described by classifying the amplifier as an AUDIO AMPLIFIER, RF AMPLIFIER, or VIDEO (WIDE-BAND) AMPLIFIER. Audio amplifiers have frequency response in the range of 15 Hz to 20 KHz. An RF amplifier has a frequency response in the range of 10 KHz to 100,000 MHz. A video (wide-band) amplifier has a frequency response of 10 Hz to 6 MHz.

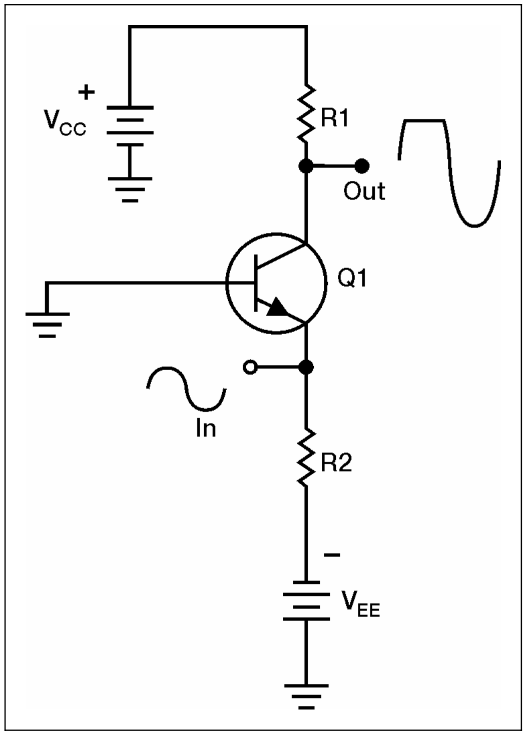


CLASS OF OPERATION **-** the class of operation of a transistor amplifier is determined by the percent of time that current flows through the transistor in relation to the input signal.

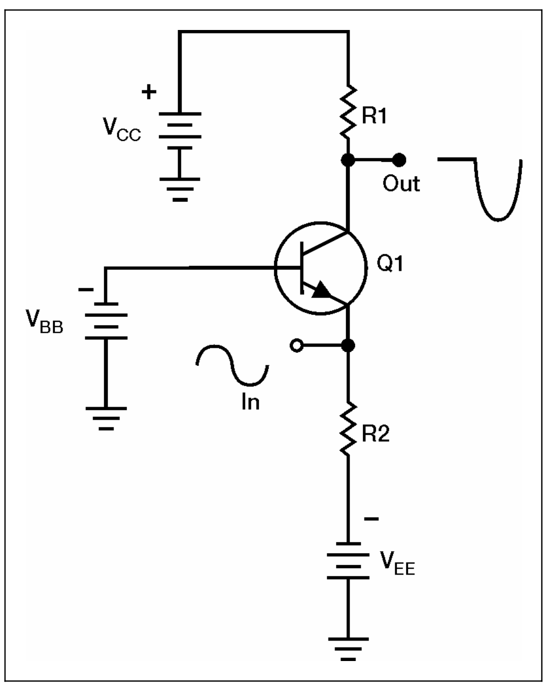
CLASS A OPERATION **-** where transistor current flows for 100 percent (360º) of the input signal. Class A operation is the least efficient class of operation, but provides the best fidelity.



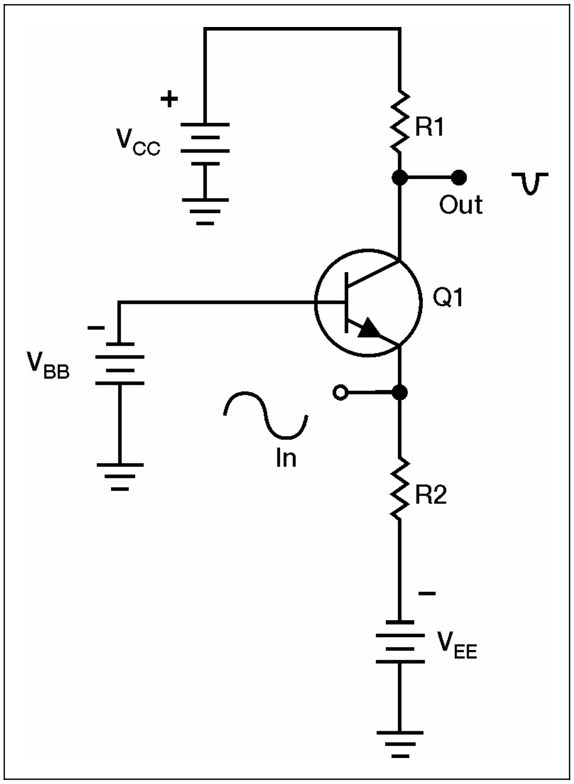
CLASS AB OPERATION - where transistor current flows for more than 50 percent but less than 100 percent of the input signal.



CLASS B OPERATION - where transistor current flows for 50 percent of the input signal.

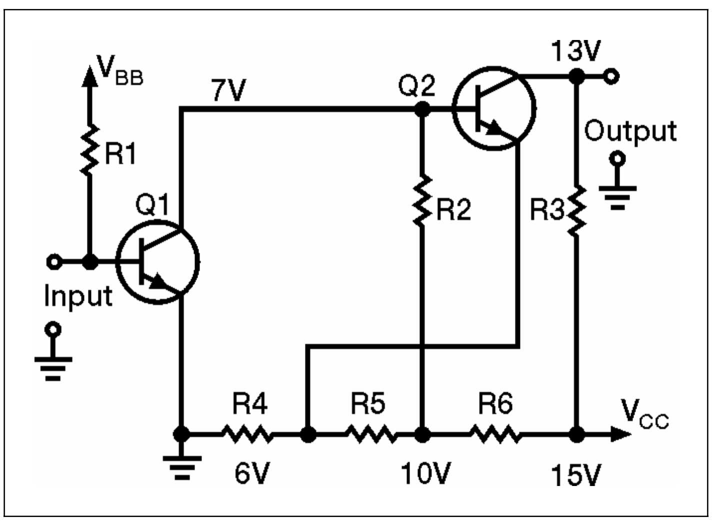


CLASS C OPERATION - where transistor current flows for less than 50 percent of the input signal. Class C operation is the most efficient class of operation.

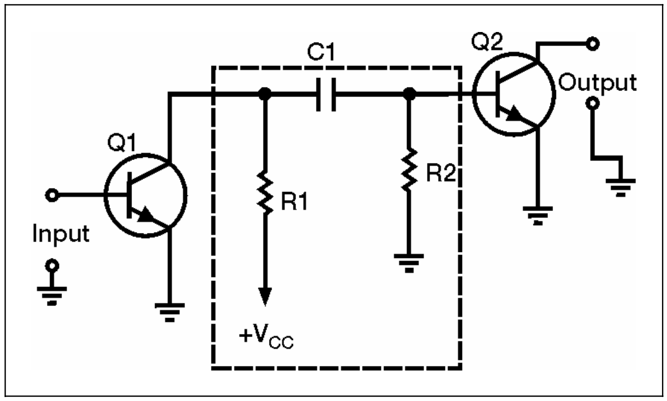


COUPLING - used to transfer a signal from one stage to another.

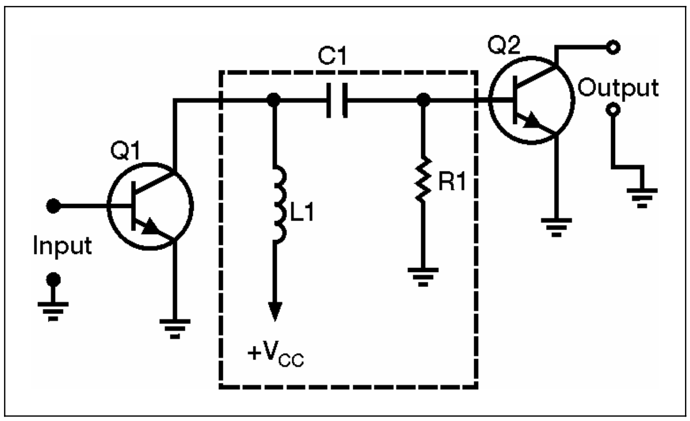
DIRECT COUPLING - the connection of the output of one stage directly to the input of the next stage. This method is not used very often due to the complex power supply requirements and impedance-matching problems.



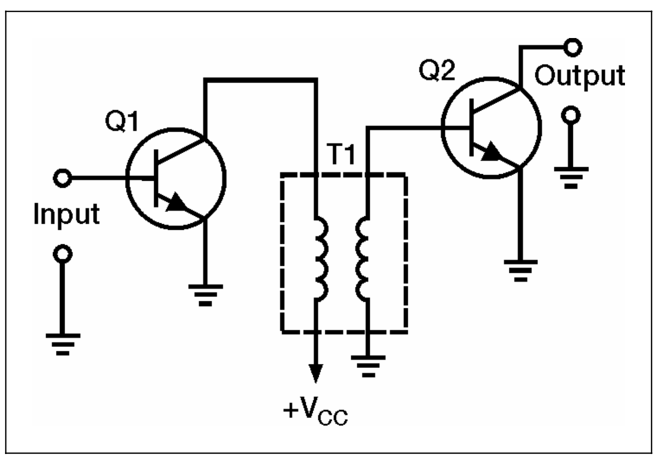
RC COUPLING - the most common method of coupling and uses a coupling capacitor and signal-developing resistors.



IMPEDANCE COUPLING - uses a coil as a load for the first stage but otherwise functions just as RC coupling. Impedance coupling is used at high frequencies.

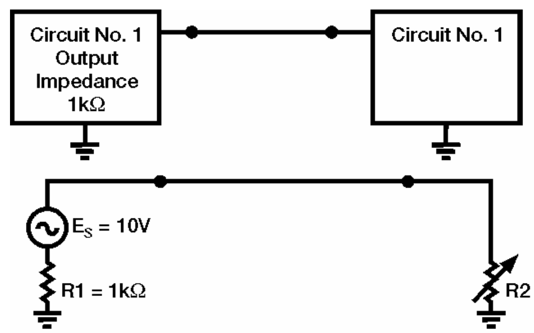


TRANSFORMER COUPLING - uses a transformer to couple the signal from one stage to the next. Transformer coupling is very efficient and the transformer can aid in impedance matching.



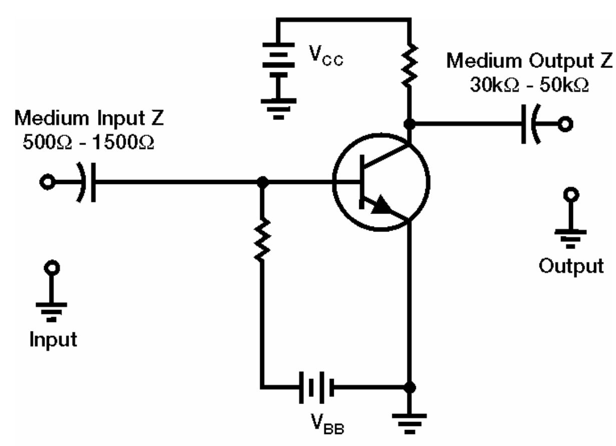
MAXIMUM POWER TRANSFER **-** occurs between two circuits when the output impedance of the first circuit matches the input impedance of the second circuit.

MAXIMUM VOLTAGE INPUT SIGNAL **-** is present when the input impedance of the second circuit is larger than the output impedance of the first circuit (mismatched).



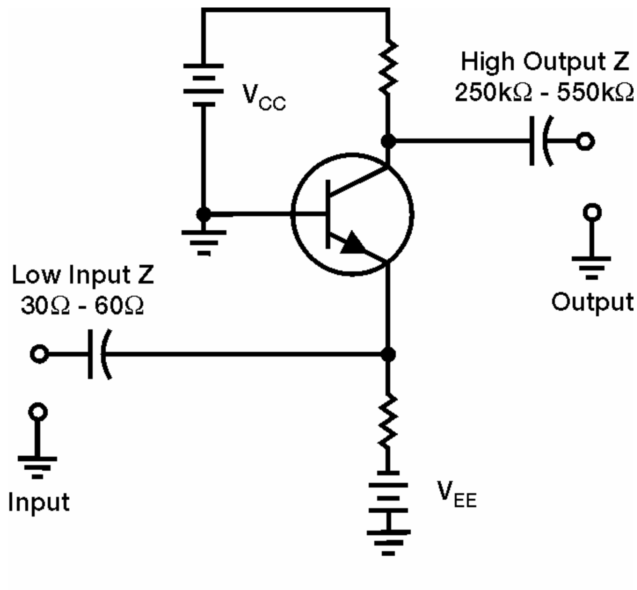
R2	I	E_{R2}	P_{R1}	P_{R2}
100Ω	9mA	900mV	82.6mW	8.3mW
200Ω	8.3mA	1.67V	69.4mW	13.9mW
500Ω	6.7mA	3.33V	44.4mW	22.2mW
1kΩ	5mA	5V	25mW	25mW
2kΩ	3.3mA	6.67V	11.1mW	22.2mW
5kΩ	1.7mA	8.33V	2.7mW	13.9mW
10kΩ	.9mA	9.09V	.9mW	8.3mW

COMMON EMITTER **-** this configuration of a transistor amplifier has medium input and medium output impedance.



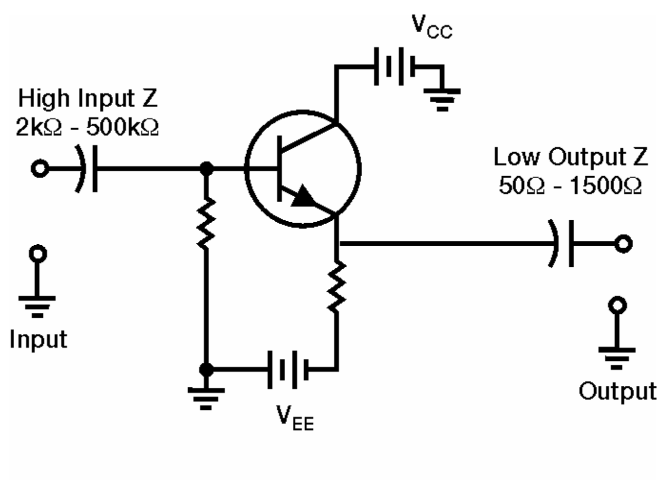
Common Emitter

COMMON BASE **-** this configuration of a transistor amplifier has low input and high output impedance.



Common Base

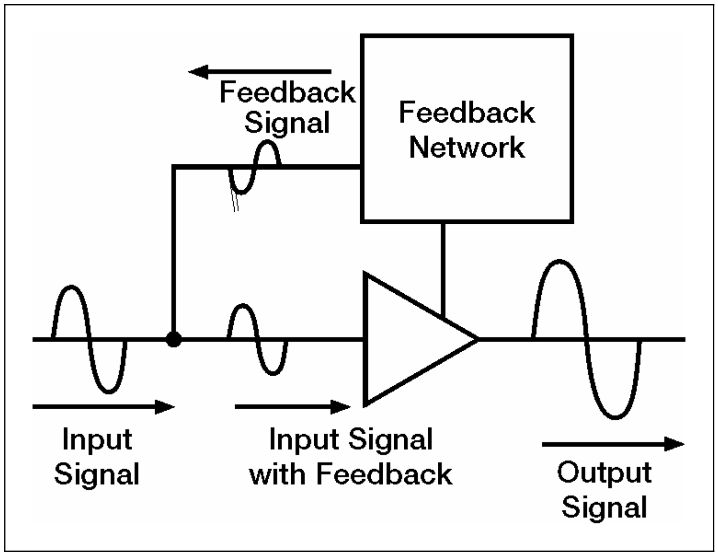
COMMON COLLECTOR (EMITTER FOLLOWER) **-** this configuration of a transistor amplifier has high input and low output impedance.



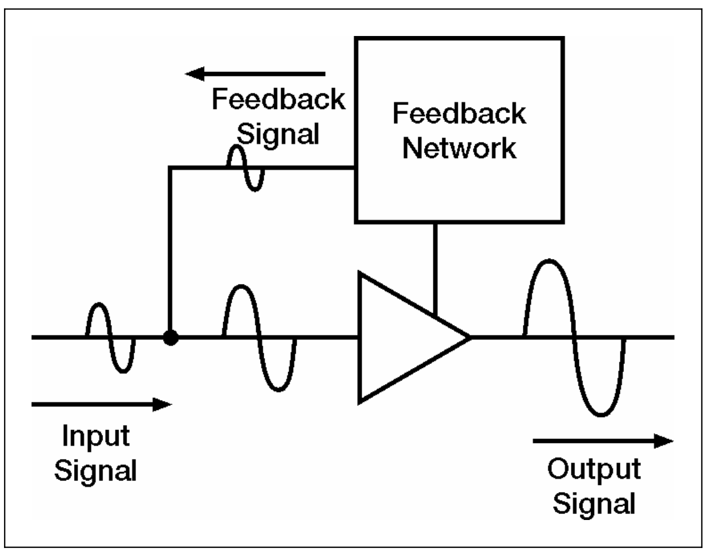
Common Collector

FEEDBACK **-** the process of coupling a portion of the output signal back to the input of an amplifier.

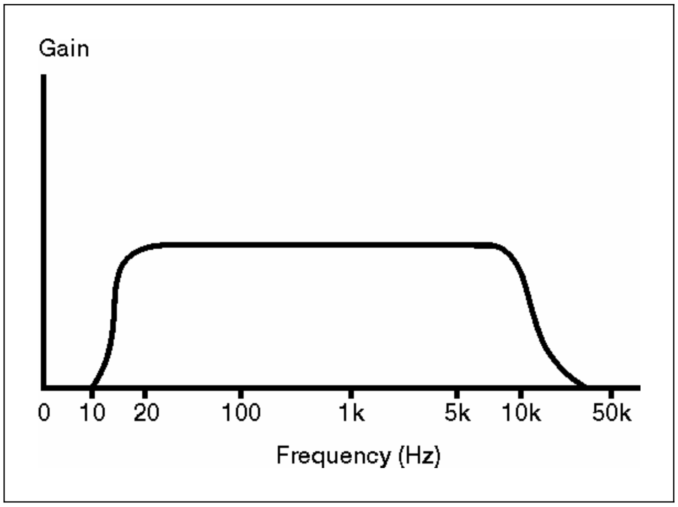
POSITIVE (REGENERATIVE) FEEDBACK - provided when the feedback signal is in phase with the input signal. Positive feedback increases the gain of an amplifier.



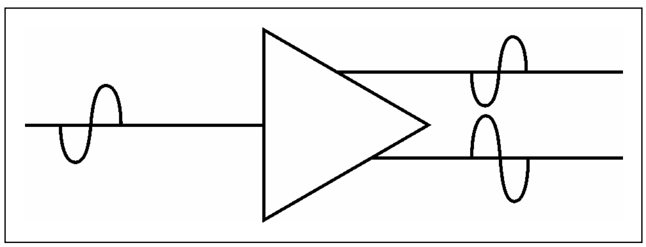
NEGATIVE (DEGENERATIVE) FEEDBACK - provided when the feedback signal is 180° out of phase with the input signal. Negative feedback decreases the gain of an amplifier but improves fidelity and may increase the frequency response of the amplifier.



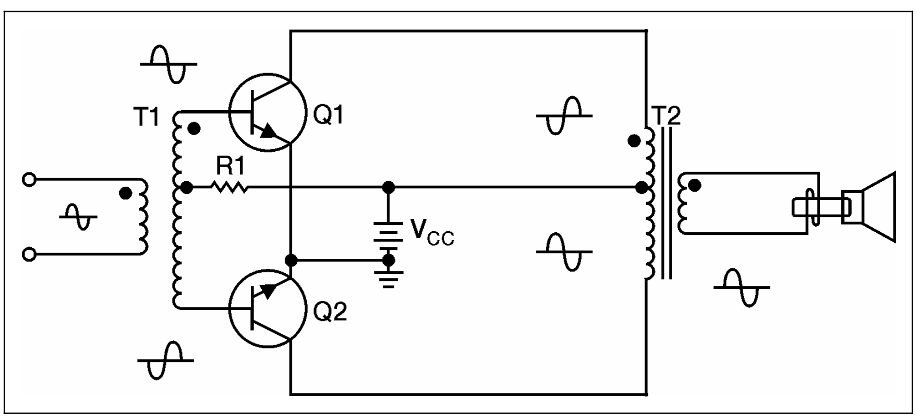
IDEAL FREQUENT RESPONSE - of an audio amplifier is equal gain from 15 Hz to 20 KHz with very low gain outside of those limits.



PHASE SPLITTER - provides two output signals that are equal in amplitude but different in phase from a single-input signal. Phase splitters are often used to provide input signals to a push-pull amplifier.



PUSH-PULL AMPLIFIER - uses two transistors whose output signals are added together to provide a larger gain (usually a power gain) than a single transistor could provide. Push-pull amplifiers can be operated class A or class B and are usually used as the final output or driver stage of a device.



CHAPTER 5
CHECK-ON-LEARNING QUESTIONS

When you are satisfied that you have answered every question to the best of your ability, check your answers using Appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. What is amplification?

2. What is the definition of an amplifier?

3. Why do electronic devices use amplifiers?

4. In what two ways are amplifiers classified?

5. What type of amplifier would be used to amplify the signal from a radio antenna?

6. What do you compare to determine if an amplifier is voltage or power?

7. What is another name given to a video amplifier?

8. What type of device is a transistor amplifier?

9. What determines the class of operation of an amplifier?

10. What are the four classes of operation of a transistor amplifier?

11. What class of amplifier operates on 50 percent of the input signal?

12. Why is class C operation more efficient than any other class of operation?

13. What happens when stages of amplification are added?

14. What do you call the process of transferring energy between circuits?

15. What are four of the most common methods of coupling amplifiers?

16. What is the major problem with direct coupling?

17. What is the most common form of coupling?

18. What type coupling would be most useful for an audio amplifier between the first and second stages?

19. The most efficient device is one that does the job with the least amount of what?

20. How do you compute the value of impedance?

21. What is feedback?

22. What are two types of feedback?

23. The amount of the output signal from an amplifier is dependent on what?

24. What is the most common configuration for transistor amplifiers?

25. What controls the current through the transistor?

26. How do you stop negative feedback caused by the emitter resistor?

27. What type of feedback is used to improve the fidelity of an amplifier by limiting the input signal?

28. What is the difference between an audio amplifier and other amplifiers?

29. What is a phase splitter?

30. The phase splitter combines the qualities of what two configurations?

31. What is one use of phase splitters?

32. What class(es) of operation can be used with a push-pull amplifier to provide good fidelity output signals?

Chapter 6

Video and Radio Frequency Amplifiers

LEARNING OBJECTIVES

Learning objectives serve as a preview of the information you are expected to learn in this chapter. The comprehensive check-on-learning questions, found at the end of the chapter, are based on the objectives. Upon completion of this chapter, you will be able to perform the following learning objectives:

- Define the term "bandwidth of an amplifier."
- Determine the upper and lower frequency limits of an amplifier from a frequency-response curve.
- List two techniques used to increase the high-frequency response for a video amplifier.
- State one technique used to increase the low-frequency response of a video amplifier.
- Identify the purpose of various components on a schematic of a complete typical video amplifier circuit.
- State the purpose of a frequency-determining network in an RF amplifier.
- State one method by which an RF amplifier can be neutralized.
- Identify the purpose of various components on a schematic of a complete typical RF amplifier.

INTRODUCTION TO VIDEO AND RADIO FREQUENCY AMPLIFIERS

6-1. In this chapter you will be given information on the frequency response of amplifiers as well as specific information on video and RF amplifiers. For all practical purposes, all the general information you learned about audio amplifiers in chapter 5 will apply to the video and RF amplifiers.

6-2. You need to learn about video and RF amplifiers and understand these circuits because you will probably be involved in working on equipment in which these circuits are used. Many of the circuits shown in this chapter and chapter 7 are incomplete and would not be used in actual equipment. For example, the complete biasing network may not be shown. This is done so you can concentrate on the concepts being presented without being overwhelmed by an abundance of circuit elements. The information that is presented in this chapter is real, practical information about video and RF amplifiers. It is the kind of information that you will use in working with these circuits. Engineering information (such as design specifications) will not be presented because it is not needed to understand the concepts that you need to perform the job of circuit analysis and repair.

6-3. The term "video" comes from video amplifiers that are used to amplify signals that represent video information. Video is the "picture" portion of a television signal. The "sound" portion is audio. Video signals are not only used for television, they are also used for radar systems. Therefore, radar systems use video amplifiers. Video amplifiers are also used in video recorders and some communication and control devices. In addition to using video amplifiers, televisions use RF amplifiers. Many other devices also use RF amplifiers (such as radios, navigational devices, and communications systems). Almost any device that uses broadcast or transmitted information will use an RF amplifier.

6-4. Remember, RF amplifiers are used to amplify signals between 10 KHz and 100,000 MHz (not this entire band of frequencies, but any band of frequencies within these limits). Therefore, any device that uses frequencies between 10 KHz and 100,000 MHz will most likely use an RF amplifier.

AMPLIFIER FREQUENCY RESPONSE

6-5. You will need to learn a little more about the frequency response of an amplifier and frequency-response curves before you learn about video and RF amplifiers. In chapter 5 you were shown the frequency-response curve of an audio amplifier. There is a frequency-response curve associated with every amplifier. Frequency-response curves are used because they provide a "picture" of the performance of an amplifier at various frequencies. You will probably never have to draw a frequency-response curve. However, in order to use one, you should know how a frequency-response curve is created. The amplifier for which the frequency-response curve is created is tested at various frequencies. At each frequency, the input signal is set to some predetermined level of voltage (or current). This same voltage (or current) level for all of the input signals is used to provide a standard input and to allow evaluation of the output of the circuit at each of the frequencies tested. For each of these frequencies, the output is measured and marked on a graph. The graph is marked "frequency" along the horizontal axis and "voltage" or "current" along the vertical axis. When points have been plotted for all of the frequencies tested, the points are connected to form the frequency-response curve. The shape of the curve represents the frequency response of the amplifier.

6-6. Some amplifiers should be "flat" across a band of frequencies. In other words, for every frequency within the band, the amplifier should have equal gain (equal response). For frequencies outside the band, the amplifier gain will be much lower. For other amplifiers, the desired frequency response is different. For example, perhaps the amplifier should have high gain at two frequencies and low gain for all other frequencies. The frequency-response curve for this type of amplifier would show two "peaks." In other amplifiers the frequency-response curve will have one peak indicating high gain at one frequency and lower gain at all others.

6-7. Figure 6-1 shows a frequency-response curve. This is the frequency-response curve for an audio amplifier as described in chapter 5. It is "flat" from 15 Hz to 20 KHz. Also notice that the lower frequency limit is labeled f_1 and the upper frequency limit is labeled f_2. Notice also the portion inside the frequency-response curve marked "BANDWIDTH."

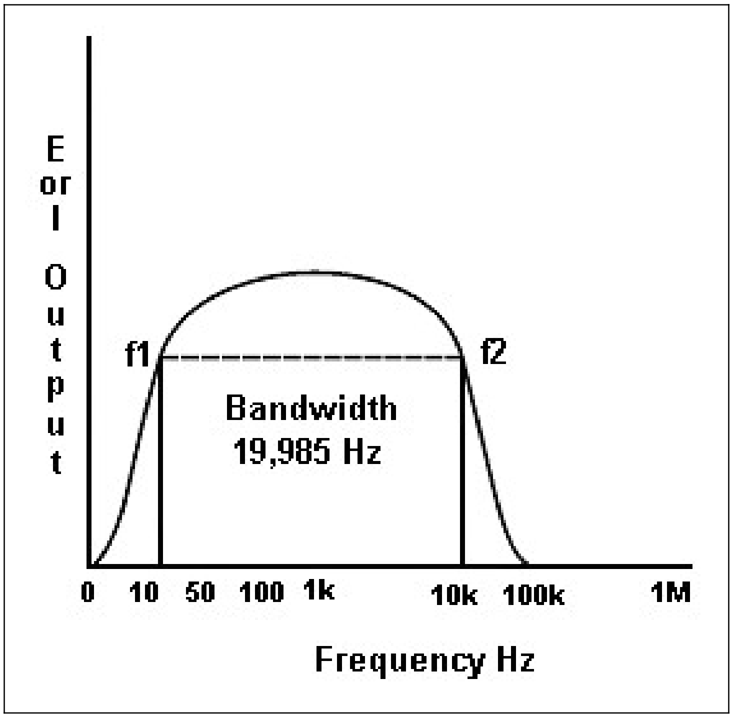


Figure 6-1. Frequency-response Curve of Audio Amplifier

BANDWIDTH OF AN AMPLIFIER

6-8. The bandwidth represents the amount or "width" of frequencies, or the "band of frequencies," that the amplifier is most effective in amplifying. However, the bandwidth is not the same as the band of frequencies that is amplified. The bandwidth of an amplifier is the difference between the frequency limits of the amplifier. For example, the band of frequencies for an amplifier may be from 10 KHz to 30 KHz. In this case, the bandwidth would be 20 KHz. As another example, if an amplifier is designed to amplify frequencies between 15 Hz and 20 KHz, the bandwidth will be equal to 20 KHz minus 15 Hz or 19,985 Hz (see Figure 6-1). The following shows how to compute bandwidth:

$$BW = f_2 - f_1$$

$$BW = 20\text{ KHz} - 15\text{ Hz}$$

$$BW = 20{,}000\text{ Hz} - 15\text{ Hz}$$

$$BW = 19{,}985\text{ Hz}$$

6-9. Also notice in Figure 6-1 that the frequency-response curve shows output voltage (or current) against frequency. The lower and upper frequency limits (f_1 and f_2) are also known as HALF-POWER POINTS. The half-power points are the points at which the output voltage (or current) is 70.7 percent of the maximum output voltage (or current). Any frequency that produces less than 70.7 percent of the maximum output voltage (or current) is outside the bandwidth and, in most cases, is not considered a usable output of the amplifier. The reason these points are called "half-power points" is that the true output power will be half (50 percent) of the maximum true output power when the output voltage (or current) is 70.7 percent of the maximum output voltage (or current).

6-10. In an AC circuit, true power is calculated using the resistance (R) of the circuit, not the impedance (Z). If the circuit produces a maximum output voltage of 10 volts across a 50-ohm load, use the following formula:

$$\text{True Power} = \frac{E^2}{R}$$

$$\text{True Power} = \frac{(10\ V)^2}{50\ \Omega}$$

$$\text{True Power} = \frac{100}{50}\ \text{watts}$$

$$\text{True Power} = 2\ \text{watts}$$

NOTE: All calculations are rounded off to two decimal places.

When the output voltage drops to 70.7 percent of the maximum voltage of 10 volts, then use the following formula:

$$\text{True Power} = \frac{E^2}{R}$$

$$\text{True Power} = \frac{(7.07\ V)^2}{50\ \Omega}$$

$$\text{True Power} = \frac{50}{50}\ \text{watts}$$

$$\text{True Power} = 1\ \text{watt}$$

6-11. As you can see, the true power is 50 percent (half) of the maximum true power when the output voltage is 70.7 percent of the maximum output voltage. However, if you are using the output current of the above circuit, the maximum current would be as follows:

$$.2\ \text{amp}\ (\frac{10V}{50\Omega} = .2\,A)$$

The calculations are as follows:

True Power = I^2R

True Power = $(.2\ A)^2\ (50\Omega)$

True Power = (.04 x 50) watts

True Power = 2 watts

At 70.7 percent of the output current (.14 A) use the following formula:

True Power = I^2R

True Power = $(.14\ A)^2\ (50\Omega)$

True Power = (.02 x 50) watts

True Power = 1 watt

6-12. In Figure 6-1, the two points marked f_1 and f_2 will enable you to determine the frequency-response limits of the amplifier. In this case, the limits are 15 Hz and 20 KHz. You should now know how a frequency-response curve could enable you to determine the frequency limits and the bandwidth of an amplifier.

READING AMPLIFIER FREQUENCY-RESPONSE CURVES

6-13. Figure 6-2 shows the frequency-response curves for four different amplifiers. View (A) is the same frequency-response curve as shown in Figure 6-1.

6-14. Figure 6-2, view (B) is the frequency-response curve of an amplifier that would also be classified as an audio amplifier, even though the curve is not “flat” from 15 Hz to 20 KHz and does not drop off sharply at the frequency limits. From the curve, you can see that the lower frequency limit of this amplifier (f_1) is 100 Hz. The upper frequency limit (f_2) is 10 KHz. Therefore, the bandwidth of this amplifier must be 10 KHz minus 100 Hz or 9,900 Hz. Most amplifiers will have a frequency-response curve shaped like view (B) if nothing is done to modify the frequency-response characteristics of the circuit.

6-15. Figure 6-2, view (C) shows the frequency-response curve for an RF amplifier. The frequency limits of this amplifier are 100 KHz (f_1) and 1 MHz (f_2). Therefore, the bandwidth of this amplifier is 900 KHz.

6-16. Figure 6-2, view (D) shows another audio amplifier. This time the frequency limits are 30 Hz (f_1) and 200 Hz (f_2). The bandwidth of this amplifier is only 170 Hz. The important thing to notice in this view is that the frequency scale is different from those used in other views. Any frequency scale can be used for a frequency-response curve. The scale used would be determined by what frequencies are most useful in presenting the frequency-response curve for a particular amplifier.

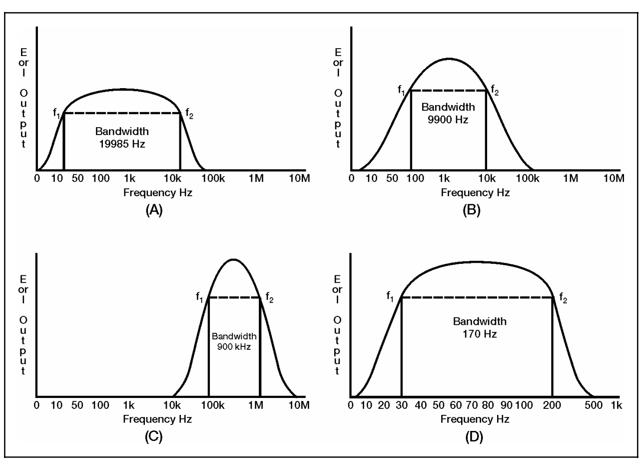


Figure 6-2. Frequency-response Curves

FACTORS AFFECTING FREQUENCY RESPONSE OF AN AMPLIFIER

6-17. Chapter 5 mentioned that an audio amplifier is limited in its frequency response. Remember that the frequency response of an AC circuit is limited by the reactive elements (capacitance and inductance) in the circuit. This is caused by the fact that the capacitive reactance and inductive reactance vary with the frequency. Therefore, the value of the reactance is determined, in part, by frequency. The following is the formula for capacitive reactance and inductive reactance:

$$X_C = \frac{1}{2\pi f C}$$

$$X_L = 2\pi f L$$

6-18. If you ignore the amplifying device (transistor, electron tube, and so on), and if the amplifier circuit is made up of resistors only, there should be no limits to the frequency response. Therefore, a totally resistive circuit would have no frequency limits. However, there is no such thing as a totally resistive circuit because circuit components almost always have some reactance. In addition to the reactance of other components in the circuit, most amplifiers use RC coupling. This means that a capacitor is used to couple the signal into and out of the circuit. There is also a certain amount of capacitance and inductance in the wiring of the circuit. The end result is that all circuits are reactive. Figure 6-3 shows amplifier circuits with the capacitance and inductance of the wiring represented as "phantom" capacitors and inductors. The reactance of the capacitors *(*X_C*)* and the inductors *(*X_L*)* are shown as "phantom" variable resistors. View (A) shows the circuit with a low-frequency input signal and view (B) shows the circuit with a high-frequency input signal.

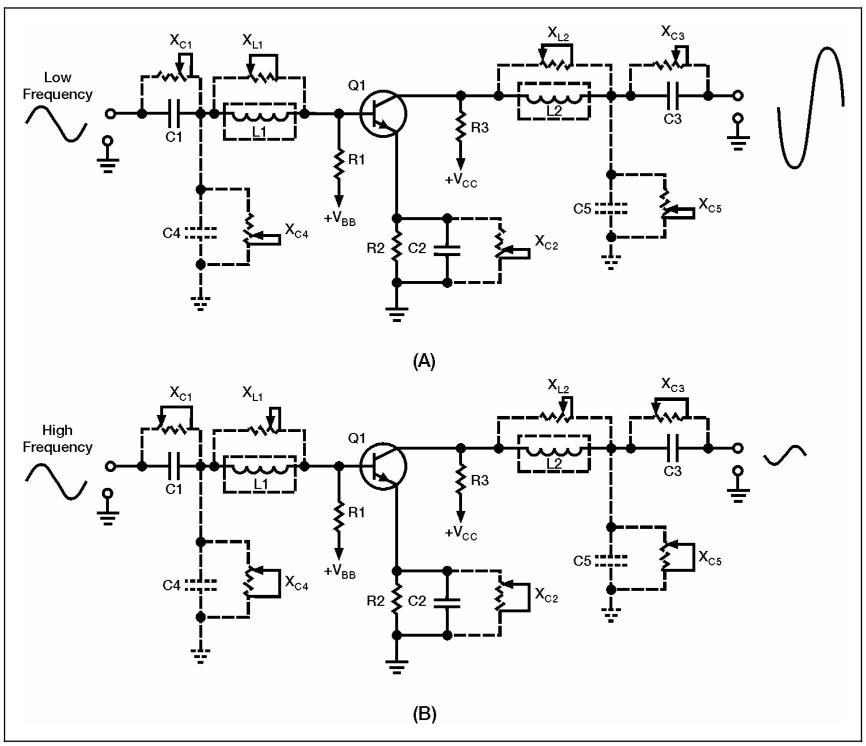


Figure 6-3. Amplifiers Showing Reactive Elements and Reactance

6-19. The actual circuit components are C1, C2, C3, R1, R2, R3, and Q1. C1 is used to couple the input signal. R1 develops the input signal. R2, the emitter resistor, is used for proper biasing and temperature stability. C2 is a decoupling capacitor for R2. R3 develops the output signal. C3 couples the output signal to the next stage. Q1 is the amplifying device.

6-20. The phantom circuit elements representing the capacitance and inductance of the wiring are L1, L2, C4, and C5. L1 represents the inductance of the input wiring. L2 represents the inductance of the output wiring. C4 represents the capacitance of the input wiring. C5 represents the capacitance of the output wiring.

6-21. Figure 6-3, view (A) shows the circuit with a low-frequency input signal. Remember that if frequency is low, capacitive reactance will be high and inductive reactance will be low. This is shown by the position of the variable resistors that represent the reactances. Notice that X_{L1} and X_{L2} are low. Therefore, they do not "drop" very much of the input and output signals. However, X_{C4} and X_{C5} are high. Therefore these reactances tend to "block" the input and output signals and keep them from going to the power supplies (V_{BB} and V_{CC}). Notice that the output signal is larger in amplitude than the input signal.

6-22. Figure 6-3, view (B) shows that the input signal is a high-frequency signal. Now X_C is low and X_L is high. X_{L1} and X_{L2} now drop part of the input and output signals. At the same time X_{C4} and X_{C5} tend to "short" or "pass" the input and output signals to signal ground. The net effect is that both the input and output signals are reduced. Notice that the output signal is smaller in amplitude than the input signal. Now you can see how the capacitance and inductance of the wiring affects an amplifier causing the output of an amplifier to be less for high-frequency signals than for low-frequency signals.

6-23. In addition to the other circuit components, an amplifying device (transistor or electronic tube) reacts differently to high frequencies than it does to low frequencies. Transistors and electronic tubes have interelectrode capacitance. Figure 6-4 shows a portion of the interelectrode capacitance of a transistor and the way in which this affects high- and low-frequency signals.

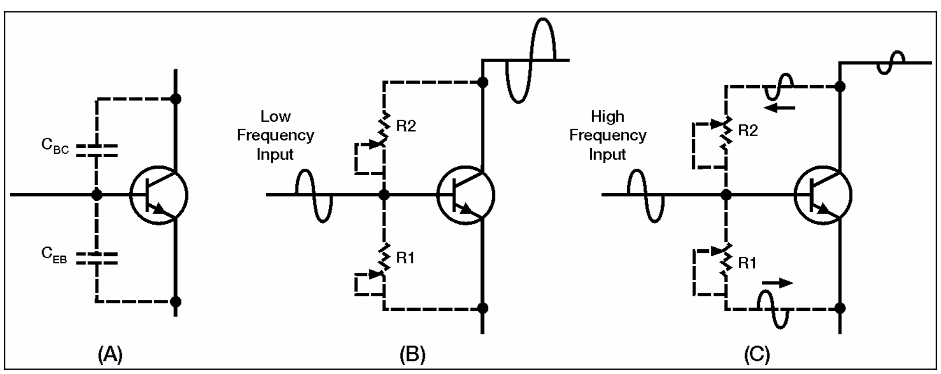


Figure 6-4. Interelectrode Capacitance of a Transistor

6-24. Figure 6-4, view (A) shows a transistor with phantom capacitors connected to represent the interelectrode capacitance. C_{EB} represents the emitter-to-base capacitance. C_{BC} represents the base-to-collector capacitance.

6-25. For simplicity, Figure 6-4 (views (B) and (C)) shows the capacitive reactance of these capacitors by variable resistors R1 (for C_{EB}) and R2 (for C_{BC}). View (B) shows the reactance as high when there is a low frequency input signal. In this case there is very little affect from the reactance on the transistor. The transistor amplifies the input signal as shown in view (B). However, when a high frequency input signal is applied to the transistor (view (C)), things are somewhat different. Now the capacitive reactance is low (as shown by the settings of the variable resistors). In this case, as the base of the transistor attempts to go positive during the first half of the input signal, a great deal of this positive signal is felt on the emitter (through R1). If both the base and the emitter go positive at the same time, there is no change in emitter-base bias and the conduction of the transistor will not change. Of course, a small amount of change does occur in the emitter-base bias, but not as much as when the capacitive reactance is higher (at low frequencies). As an output signal is developed in the collector circuit, part of this signal is fed back to the base through R2. Since the signal on the collector is 180 degrees out of phase with the base signal, this tends to drive the base negative. The effect of this is to further reduce the emitter-base bias and the conduction of the transistor. During the second half of the input signal, the same effect occurs although the polarity is reversed. The net effect is a reduction in the gain of the transistor as indicated by the small output signal. This decrease in the amplifier output at higher frequencies is caused by the interelectrode capacitance. There are certain cases in which the feedback signal caused by the interelectrode capacitance is in phase with the base signal. However, in most cases, the feedback caused by interelectrode capacitance is degenerative and is 180 degrees out of phase with the base signal as explained above.

VIDEO AMPLIFIERS

6-26. You have seen that a transistor amplifier is limited in its frequency response. Remember from chapter 5 that a VIDEO AMPLIFIER should have a frequency response of 10 Hz to 6 MHz. The following describes how it is possible to “extend” the range of frequency response of an amplifier.

HIGH-FREQUENCY COMPENSATION FOR VIDEO AMPLIFIERS

6-27. If the frequency-response range of an audio amplifier must be extended to 6 MHz for use as a video amplifier, some means must be found to overcome the limitations of the audio amplifier. You have seen that the capacitance of an amplifier circuit and the interelectrode capacitance of the transistor (or electronic tube) cause the higher frequency response to be limited.

6-28. In some ways capacitance and inductance can be thought of as opposites. As already stated; as frequency increases, capacitive reactance decreases and inductive reactance increases. Capacitance opposes changes in voltage and inductance opposes changes in current. Capacitance causes current to lead voltage and inductance causes voltage to lead current.

6-29. Frequency effects capacitive reactance and inductive reactance in opposite ways. Since it is the capacitive reactance that causes the problem with high-frequency response, inductors are added to an amplifier circuit to improve the high-frequency response. This is called HIGH-FREQUENCY COMPENSATION. Inductors (coils), when used for high-frequency compensation, are called PEAKING COILS. Peaking coils can be added to a circuit so they are in series with the output signal path or in parallel to the output signal path. Instead of only in series or parallel, a combination of peaking coils in series and parallel with the output signal path can also be used for high-frequency compensation. The

use of peaking coils will increase the frequency response of an amplifier circuit. However, it will also lower the gain of the amplifier.

Series Peaking

6-30. The use of a peaking coil in series with the output signal path is known as SERIES PEAKING. Figure 6-5 shows a transistor amplifier circuit with a series peaking coil. In the figure, R1 is the input-signal-developing resistor. R2 is used for bias and temperature stability of Q1. C1 is the bypass capacitor for R2. R3 is the load resistor for Q1 and develops the output signal. C2 is the coupling capacitor that couples the output signal to the next stage. "Phantom" capacitor C_{OUT} represents the output capacitance of the circuit, and "phantom" capacitor C_{IN} represents the input capacitance of the next stage. The capacitive reactance of C_{OUT} and C_{IN} will limit the high-frequency response of the circuit. L1 is the series peaking coil. It is in series with the output-signal path and isolates C_{OUT} from C_{IN}. R4 is called a "swamping" resistor and is used to keep L1 from overcompensating at a narrow range of frequencies. In other words, R4 is used to keep the frequency-response curve flat. If R4 were not used with L1, there could be a "peak" in the frequency-response curve.

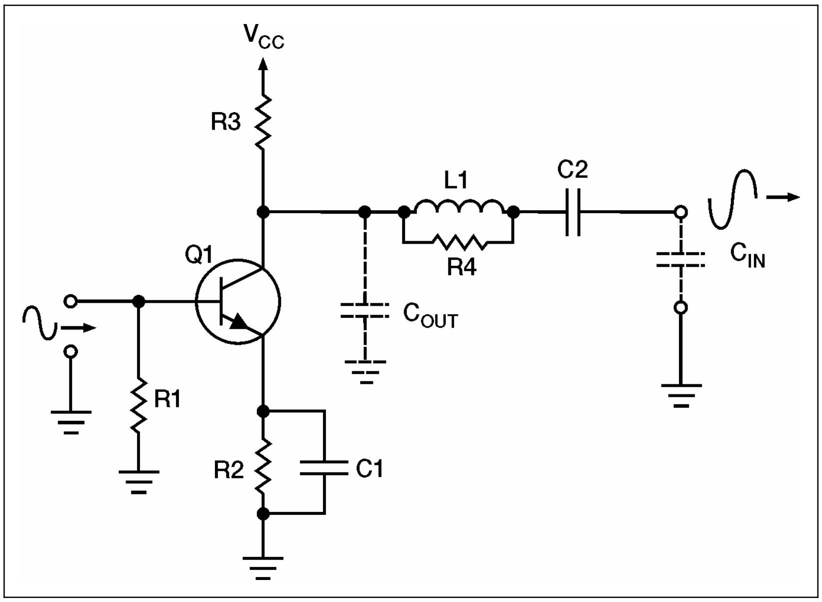


Figure 6-5. Series Peaking Coil

Shunt Peaking

6-31. If a coil is placed in parallel (shunt) with the output signal path, the technique is called SHUNT PEAKING. Figure 6-6 shows a circuit with a shunt peaking coil. R1 is the input-signal-developing resistor. R2 is used for bias and temperature stability. C1 is the bypass capacitor for R2. R3 is the load resistor for Q1 and develops the output signal. C2 is the coupling capacitor that couples the output signal to the next stage.

6-32. The "phantom" capacitor, C_T, represents the total capacitance of the circuit. Notice that it tends to couple the output signal to ground. L1 is the shunt peaking coil. While it is in series with the load resistor (R3), it is in parallel (shunt) with the output-signal path.

6-33. Since inductive reactance increases as frequency increases, the reactance of L1 develops more output signal as the frequency increases. At the same time, the capacitive

reactance of C_T is decreasing as frequency increases. This tends to couple more of the output signal to ground. The increased inductive reactance counters the effect of the decreased capacitive reactance and this increases the high-frequency response of the amplifier.

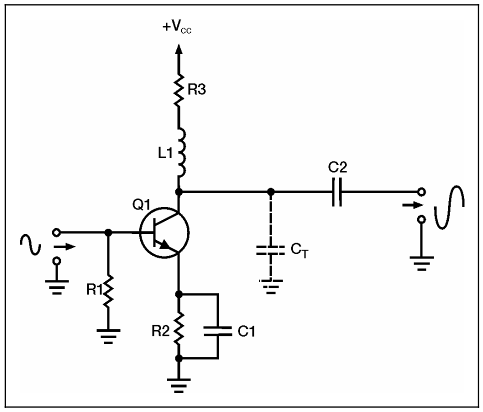


Figure 6-6. Shunt Peaking Coil

Combination Peaking

6-34. You have seen how a series peaking coil isolates the output capacitance of an amplifier from the input capacitance of the next stage. You have also seen how a shunt peaking coil will counteract the effects of the total capacitance of an amplifier. If these two techniques are used together, the combination is more effective than the use of either one alone. The use of both series and shunt peaking coils is known as COMBINATION PEAKING. Figure 6-7 shows an amplifier circuit with combination peaking. In Figure 6-7 the peaking coils are L1 and L2, L1 is a shunt peaking coil, and L2 is a series peaking coil.

6-35. The "phantom" capacitor C_T represents the total capacitance of the amplifier circuit. "Phantom" capacitor C_{IN} represents the input capacitance of the next stage. Combination peaking will easily allow an amplifier to have a high-frequency response of 6 MHz.

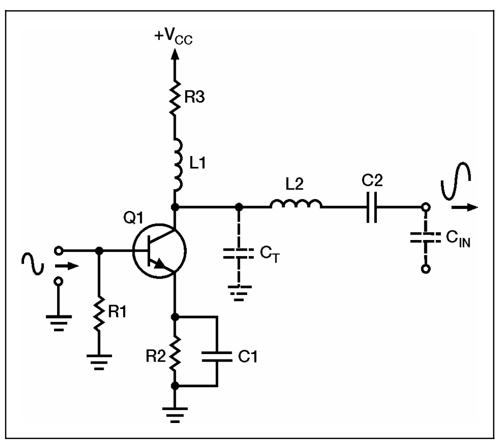


Figure 6-7. Combination Peaking

LOW-FREQUENCY COMPENSATION FOR VIDEO AMPLIFIERS

6-36. You have seen how the high-frequency response of an amplifier can be extended to 6 MHz. You should realize that it is only necessary to extend the low-frequency response to 10 Hz in order to have a video amplifier. Once again, the culprit in low-frequency response is capacitance (or capacitive reactance). However, this time the problem is the coupling capacitor between the stages.

6-37. At low frequencies the capacitive reactance of the coupling capacitor (C2 in Figure 6-7) is high. This high reactance limits the amount of output signal that is coupled to the next stage. In addition, the RC network of the coupling capacitor and signal-developing resistor of the next stage cause a phase shift in the output signal. Both of these problems (poor low-frequency response and phase shift) can be solved by adding a parallel RC network in series with the load resistor (see Figure 6-8).

6-38. The complete circuitry for Q2 is not shown in this figure, as the main concern is the signal-developing resistor (R5) for Q2. The coupling capacitor (C2) and the resistor (R5) limit the low-frequency response of the amplifier and cause a phase shift. The amount of the phase shift will depend upon the amount of resistance and capacitance. The RC network of R4 and C3 compensates for the effects of C2 and R5 and extends the low-frequency response of the amplifier.

6-39. At low frequencies, R4 adds to the load resistance (R3) and increases the gain of the amplifier. As frequency increases, the reactance of C3 decreases. C3 then provides a path around R4 and the gain of the transistor decreases. At the same time, the reactance of the coupling capacitor (C2) decreases and more signal is coupled to Q2. Since the circuit shown in Figure 6-8 has no high-frequency compensation, it would not be a very practical video amplifier.

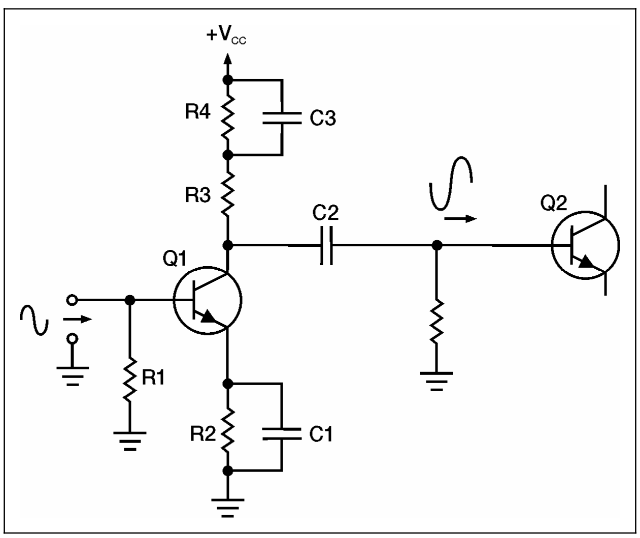


Figure 6-8. Low Frequency Compensation Network

TYPICAL VIDEO AMPLIFIER CIRCUIT

6-40. There are many different ways to build video amplifiers. The particular configuration of a video amplifier depends upon the equipment in which the video amplifier is used. Figure 6-9 shows only one of many possible video-amplifier circuits.

RADIO FREQUENCY AMPLIFIERS

6-41. You have seen the way in which a broadband or video amplifier can be constructed. RF amplifiers use different techniques, so they are very different than video amplifiers. Before you study the specific techniques used in RF amplifiers, you should review some information on the relationship between the input and output impedance of an amplifier and the gain of the amplifier stage.

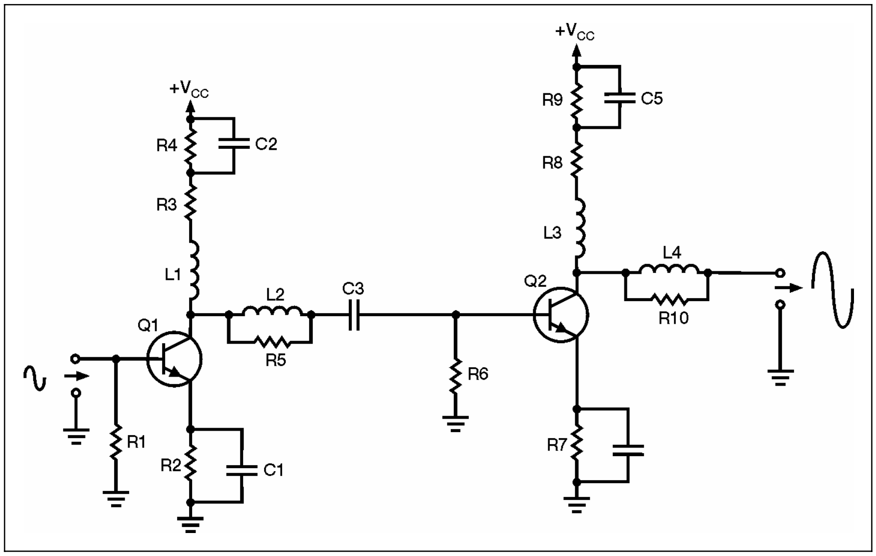


Figure 6-9. Video Amplifier Circuit

AMPLIFIER INPUT/OUTPUT IMPEDANCE AND GAIN

6-42. You should remember that the gain of a stage is calculated by using the input signals. Use the following formula to calculate the gain of a stage:

$$\text{gain} = \frac{\text{output signal}}{\text{input signal}}$$

6-43. Voltage gain is calculated using input and output voltage; current gain uses input and output current; and power gain uses input and output power. For the purposes of our discussion, we will only be concerned with voltage gain.

6-44. Figure 6-10 shows a simple amplifier circuit with the input and output signal developing impedances represented by variable resistors. In this circuit, C1 and C2 are the input and output coupling capacitors. R1 represents the impedance of the input circuit. R2 represents the input-signal-developing impedance and R3 represents the output impedance.

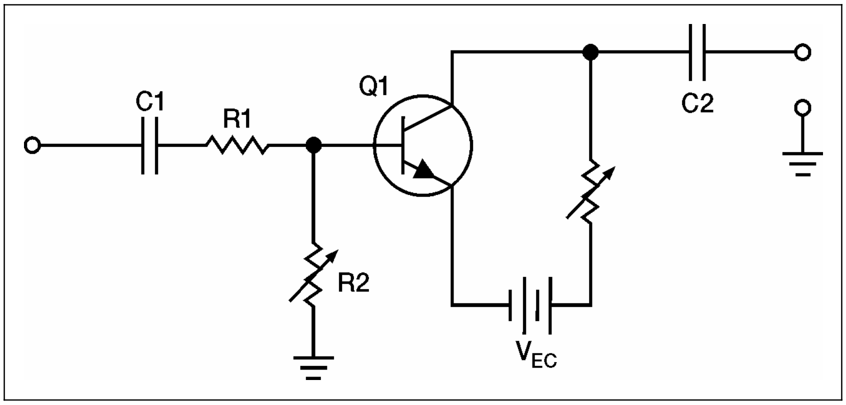


Figure 6-10. Variable Input and Output Impedances

6-45. R1 and R2 form a voltage-divider network for the input signal. When R2 is increased in value, the input signal to the transistor (Q1) increases. This causes a larger output signal and the gain of the stage increases. As R3 (output resistor) is increased in value the output signal increases. This also increases the gain of the stage. As you can see, increasing the input-signal-developing impedance, the output impedance, or both will increase the gain of the stage. Of course there are limits to this process. The transistor must not be overdriven with too high an input signal or distortion will result.

6-46. With this principle in mind, if you could design a circuit that had maximum impedance at a specific frequency (or band of frequencies), that circuit could be used in an RF amplifier. This frequency-determining network could be used as the input-signal-developing impedance, the output impedance, or both. The RF amplifier circuit would then be as shown in Figure 6-11.

6-47. In this "semi-block" diagram, C1 and C2 are the input and output coupling capacitors. R1 represents the impedance of the input circuit. The blocks marked FDN represent the frequency-determining networks. They are used as input signal developing and output impedances for Q1.

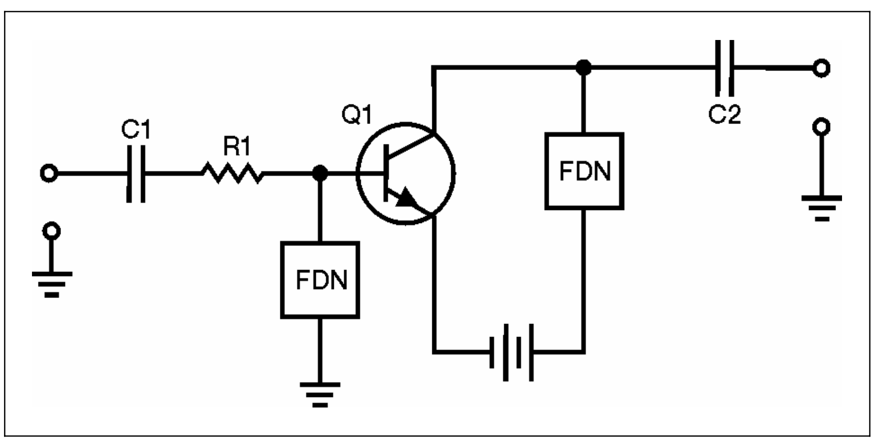


Figure 6-11. Semi-block Diagram of RF Amplifier

FREQUENCY-DETERMINING NETWORK FOR AN RF AMPLIFIER

6-48. A frequency-determining network is a circuit that provides the desired response at a particular frequency. Depending on how the frequency-determining network is used, this

response could be either maximum or minimum impedance. As you have seen, the frequency-determining network needed for an RF amplifier should have maximum impedance at the desired frequency.

6-49. Review Figure 6-12 before you look at the actual components that make up the frequency-determining network for an RF amplifier. Figure 6-12 is a simple parallel circuit. The resistors in this circuit are variable and are connected together (ganged) in such a way that as the resistance of R1 increases, the resistance of R2 decreases, and vice versa.

6-50. If each resistor has a range from 0 to 200 ohms, the following relationship will exist between the individual resistances and the resistance of the network (R_T), see Table 6-1. All values are in ohms, R_T rounded off to two decimal places. These are selected values; there are an infinite number of possible combinations.

6-51. As you can see, this circuit has maximum resistance (R_T) when the individual resistors are of equal value. If the variable resistors represented impedances and if components could be found that varied their impedance in the same way as the ganged resistors in Figure 6-12, you would have the frequency-determining network needed for an RF amplifier.

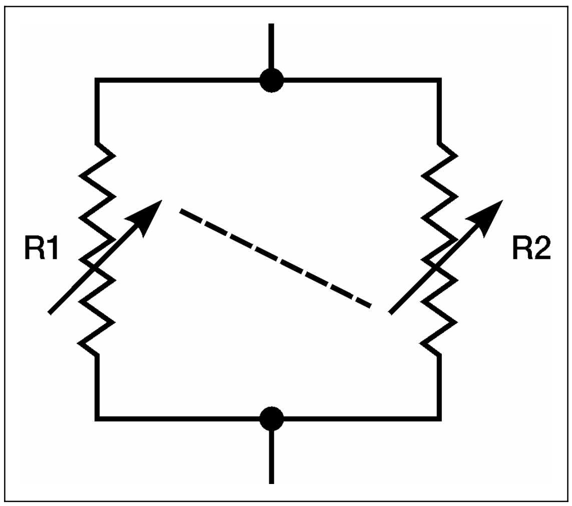


Figure 6-12. Parallel Variable Resistors (Ganged)

Table 6-1. Value Chart

R1	R2	R_T
0	200	0.00
10	190	9.50
25	175	21.88
50	150	37.50
75	125	46.88
100	100	50.00
125	75	46.88
150	50	37.50
175	25	21.88
190	10	9.50
200	0	0.00

6-52. There are components that will vary their impedance (reactance) like the ganged resistors. As you know, the reactance of an inductor and a capacitor vary as frequency changes. As frequency increases, inductive reactance increases and capacitive reactance decreases.

6-53. At some frequency, inductive and capacitive reactance will be equal. That frequency will depend upon the value of the inductor and capacitor. If the inductor and capacitor are connected as a parallel LC circuit, you will have the ideal frequency-determining network for an RF amplifier.

6-54. The parallel LC circuit used as a frequency-determining network is called a tuned circuit. This circuit is "tuned" to give the proper response at the desired frequency by selecting the proper values of inductance and capacitance. Figure 6-13 shows a circuit using this principle. The figure shows an RF amplifier with parallel LC circuits used as frequency-determining networks. This RF amplifier will only be effective in amplifying the frequency determined by the parallel LC circuits.

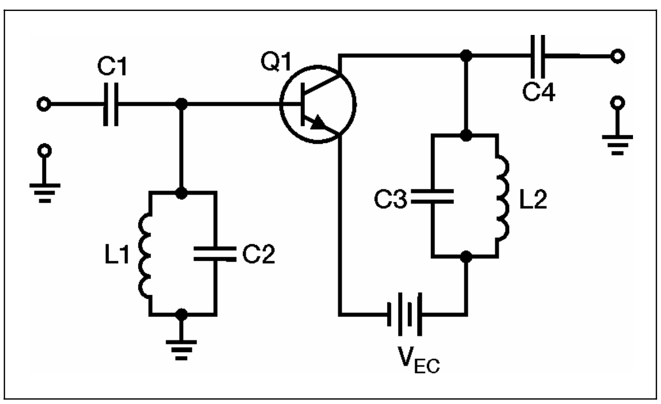


Figure 6-13. Simple RF Amplifier

6-55. In many electronic devices (such as radio or television receivers or radar systems), a particular frequency must be selected from a band of frequencies. Do this by using a separate RF amplifier for each frequency and then turning on the appropriate RF amplifier. It would be more efficient if a single RF amplifier could be "tuned" to the particular frequency as that frequency is needed. This is what happens when you select a channel on your television set or tune to a station on your radio. To accomplish this "tuning," you need only change the value of inductance or capacitance in the parallel LC circuits (tuned circuits).

6-56. In most cases, the capacitance is changed by the use of variable capacitors. The capacitors in the input and output portions of all the RF amplifier stages are ganged together in order that they can all be changed at one time with a single device (such as the tuning dial on a radio). This technique will be shown later on in a schematic.

RF AMPLIFIER COUPLING

6-57. Figure 6-13 and the other circuits you have been shown use capacitors to couple the signal into and out of the circuit (see C1 and C4 in Figure 6-13). Chapter 5 covered other methods of coupling signals from one stage to another. Transformer coupling is the most common method used to couple RF amplifiers. Transformer coupling has many advantages over RC coupling for RF amplifiers. For example, transformer coupling uses fewer components than capacitive coupling. It can also provide a means of increasing the gain of the stage by using a step-up transformer for voltage gain. If a current gain is required, a step-down transformer can be used.

6-58. Remember that the primary and secondary windings of a transformer are inductors. With these factors in mind, an RF amplifier could be constructed like the one shown in Figure 6-14. In this circuit, the secondary of T1 and capacitor C1 form a tuned circuit, which is the input-signal-developing impedance. The primary of T2 and capacitor C2 are a tuned circuit, which acts as the output impedance of Q1. T1 and T2 must be RF transformers in order to operate at RF frequencies.

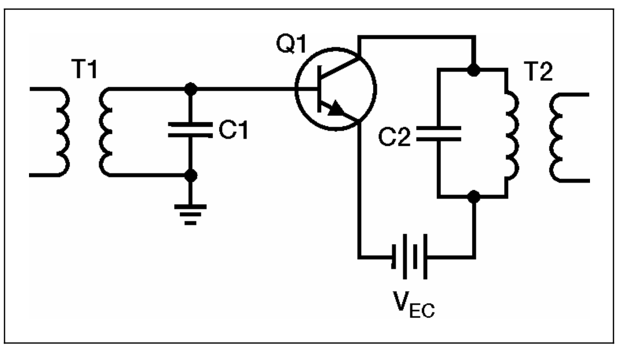


Figure 6-14. Transformer-coupled RF Amplifier

6-59. The input signal applied to the primary of T1 could come from the previous stage or from some input device, such as a receiving antenna. In either case, the input device would have a capacitor connected across a coil to form a tuned circuit. In the same way, the secondary of T2 represents the output of this circuit. A capacitor connected across the secondary of T2 would form a parallel LC network. This network could act as the input-signal-developing impedance for the next stage, or the network could represent some type of output device, such as a transmitting antenna.

6-60. The tuned circuits formed by the transformer and capacitors may not have the bandwidth required for the amplifier. In other words, the bandwidth of the tuned circuit may be too "narrow" for the requirements of the amplifier. For example, the RF amplifiers used in television receivers usually require a bandwidth of 6 MHz.

6-61. One way of "broadening" the bandpass of a tuned circuit is to use a swamping resistor. This is similar to the use of the swamping resistor that was shown with the series peaking coil in a video amplifier. A swamping resistor connected in parallel with the tuned circuit will cause a much broader bandpass.

6-62. Another technique used to broaden the bandpass involves the amount of coupling in the transformers. For transformers, the term "coupling" refers to the amount of energy transferred from the primary to the secondary of the transformer. This depends upon the number of flux lines from the primary that intersect, or cut, the secondary. When more flux lines cut the secondary, more energy is transferred. Coupling is mainly a function of the space between the primary and secondary windings. A transformer can be coupled in the following ways:

- Loosely coupled (having little transfer of energy).
- Optimum coupled (just the right amount of energy transferred).
- Over-coupled (to the point that the flux lines of primary and secondary windings interfere with each other).

6-63. Figure 6-15 shows the effect of coupling on frequency response when parallel LC circuits are made from the primary and secondary windings of transformers. In view (A), the transformer is loosely coupled (the frequency-response curve shows a narrow bandwidth). In view (B) the transformer has optimum coupling (the bandwidth is wider and the curve is relatively flat). In view (C) the transformer is over coupled (the frequency-response curve shows a broad bandpass, however the curve "dips" in the middle showing that these frequencies are not developed as well as others in the bandwidth).

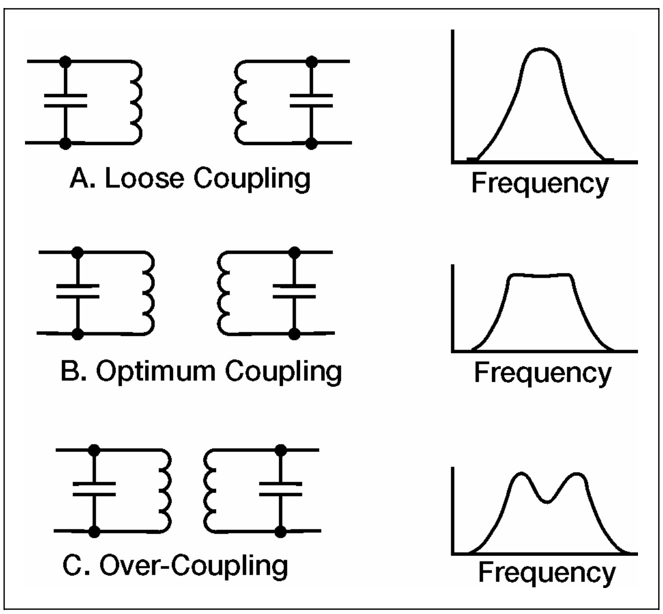


Figure 6-15. Effect of Coupling on Frequency Response

6-64. Optimum coupling will usually provide the necessary bandpass for the frequency-determining network (and therefore the RF amplifier). For some uses, such as RF amplifiers in a television receiver, the bandpass available from optimum coupling is not wide enough. In these cases, a swamping resistor, as mentioned earlier, will be used with the optimum coupling to broaden the bandpass.

COMPENSATION OF RF AMPLIFIERS

6-65. The frequencies at which RF amplifiers operate are so high that certain problems exist. One of these problems is the loss that can occur in a transformer at these high frequencies. Another problem is with interelectrode capacitance in the transistor. The process of overcoming these problems is known as compensation.

Transformers in RF Amplifiers

6-66. TC 9-60 states that the losses in a transformer are classified as copper loss, eddy-current loss, and hysteresis loss. Copper loss is not affected by frequency, as it depends upon the resistance of the winding and the current through the winding. Similarly, eddy-current loss is mostly a function of induced voltage rather than the frequency of that voltage. However, hysteresis loss increases as frequency increases.

6-67. Hysteresis loss is caused by the realignment of the magnetic domains in the core of the transformer each time the polarity of the magnetic field changes. As the frequency of the AC increases, the number of shifts in the magnetic field also increases (two shifts for each cycle of AC). Therefore, the “molecular friction” increases and the hysteresis loss is greater. This increase in hysteresis loss causes the efficiency of the transformer (and therefore the amplifier) to decrease. The energy that goes into hysteresis loss is taken away from energy that could go into the signal.

6-68. RF transformers, specially designed for use with RF, are used to correct the problem of excessive hysteresis loss in the transformer of an RF amplifier. The windings of RF transformers are wound onto a tube of nonmagnetic material and the core is either powdered iron or air. These types of cores also reduce eddy-current loss.

Neutralization of RF Amplifiers

6-69. The problem of interelectrode capacitance in the transistor of an RF amplifier is solved by neutralization. Neutralization is the process of counteracting or “neutralizing” the effect of interelectrode capacitance.

6-70. Figure 6-16 shows the effect of the base-to-collector interelectrode capacitance in an RF amplifier. The “phantom” capacitor (C_{BC}) represents the interelectrode capacitance between the base and the collector of Q1. This is the interelectrode capacitance that has the most effect in an RF amplifier. As you can see, C_{BC} causes a degenerative (negative) feedback that decreases the gain of the amplifier.

6-71. Remember, using positive feedback can counteract (neutralize) unwanted degenerative feedback. This is exactly what is done to neutralize an RF amplifier. Positive feedback is accomplished by the use of a feedback capacitor. This capacitor must feed back a signal that is in phase with the signal on the base of Q1. Figure 6-17 shows one method on how this is done.

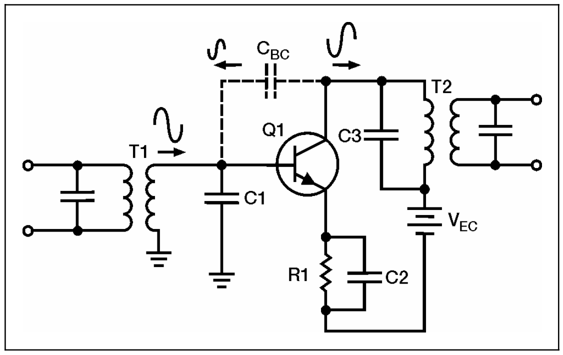


Figure 6-16. Interelectrode Capacitance in an RF Amplifier

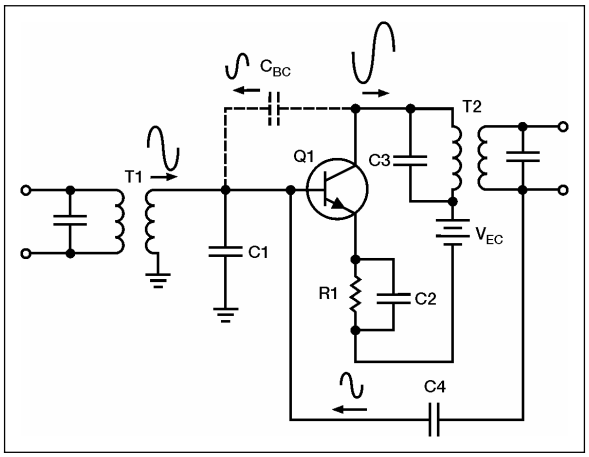


Figure 6-17. Neutralized RF Amplifier

6-72. In Figure 6-17, a feedback capacitor (C4) has been added to neutralize the amplifier. This solves the problem of unwanted degenerative feedback. Except for capacitor C4, this circuit is identical to the circuit shown in Figure 6-16. When C_{BC} causes regenerative feedback, C4 will still neutralize the amplifier. This is true because C4 always provides a feedback signal that is 180 degrees out of phase with the feedback signal caused by C_{BC}.

TYPICAL RF AMPLIFIER CIRCUITS

6-73. You will see many different RF amplifiers in many different pieces of equipment. The particular circuit configuration used for an RF amplifier will depend upon how that amplifier is used.

6-74. Figure 6-18 is the schematic diagram of a typical RF amplifier that is used in an AM radio receiver. In Figure 6-18, the input circuit is the antenna of the radio (L1—a coil) that forms part of an LC circuit that is tuned to the desired station by variable capacitor C1. L1 is wound on the same core as L2, which couples the input signal through C2 to the transistor (Q1). R1 is used to provide proper bias to Q1 from the base power supply (V_{BB}). R2 provides proper bias to the emitter of Q1 and C3 is used to bypass R2. The primary of T1 and capacitor C4 form a parallel LC circuit, which acts as the load for Q1. This LC circuit is tuned by C4, which is ganged to C1 allowing the antenna and the LC circuit to be tuned together. The primary of T1 is center-tapped to provide proper impedance matching with Q1.

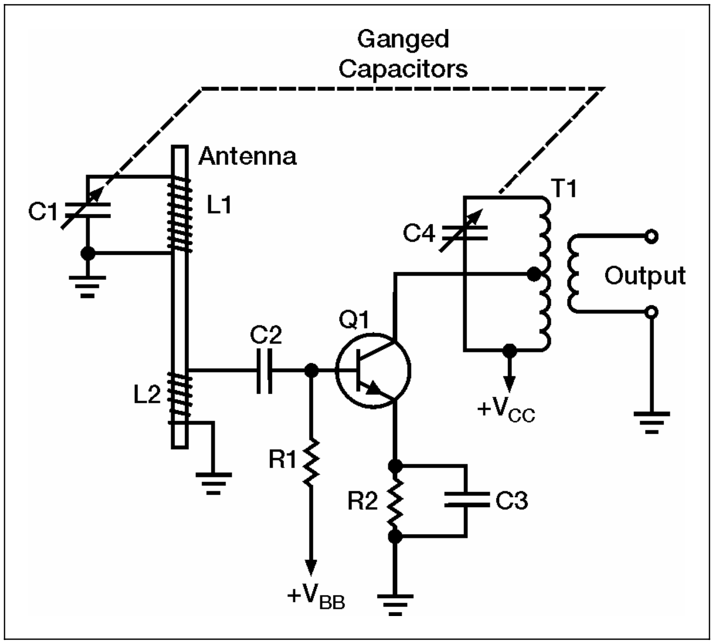


Figure 6-18. Typical RF Amplifier for AM Radio Receiver

6-75. You may notice that no neutralization is shown in this circuit. This circuit is designed for the AM broadcast band (535 KHz to 1605 KHz). At these relatively low RF frequencies the degenerative feedback caused by base-to-collector interelectrode capacitance is minor. Therefore, the amplifier does not need neutralization.

6-76. Figure 6-19 is a typical RF amplifier used in a VHF television receiver. The input signal developing circuit for this amplifier is made up of L1, C1, and C2. The inductor tunes the input signal developing circuit for the proper TV channel (L1 can be switched out of the circuit and another inductor switched into the circuit by the channel selector). R1 provides proper bias to Q1 from the base supply voltage (V_{BB}). Q1 is the transistor. Notice that the case of Q1 (the dotted circle around the transistor symbol) is shown grounded. The case must be grounded because of the high frequencies (54 MHz to 217 MHz) used by the circuit. R2 provides proper bias from the emitter of Q1 and C3 is used to bypass R2. C5 and L2 are a parallel LC circuit that acts as the load for Q1. The LC circuit is tuned by L2 that is switched into and out of the LC circuit by the channel selector. L3 and C6 are a parallel LC circuit that develops the signal for the next stage. The parallel LC circuit is tuned by L3 that is switched into and out of the LC circuit by the channel selector along with L1 and L2 (L1, L2, and L3 are actually part of a bank of inductors). L1, L2, and L3 are in the circuit when the channel selector is on channe12. For other channels, another group of three inductors would be used in the circuit. R3 develops a signal that is fed through C4 to provide neutralization. This counteracts the effects of the interelectrode capacitance from the base to the collector of Q1. C7 is used to isolate the RF signal from the collector power supply (V_{CC}).

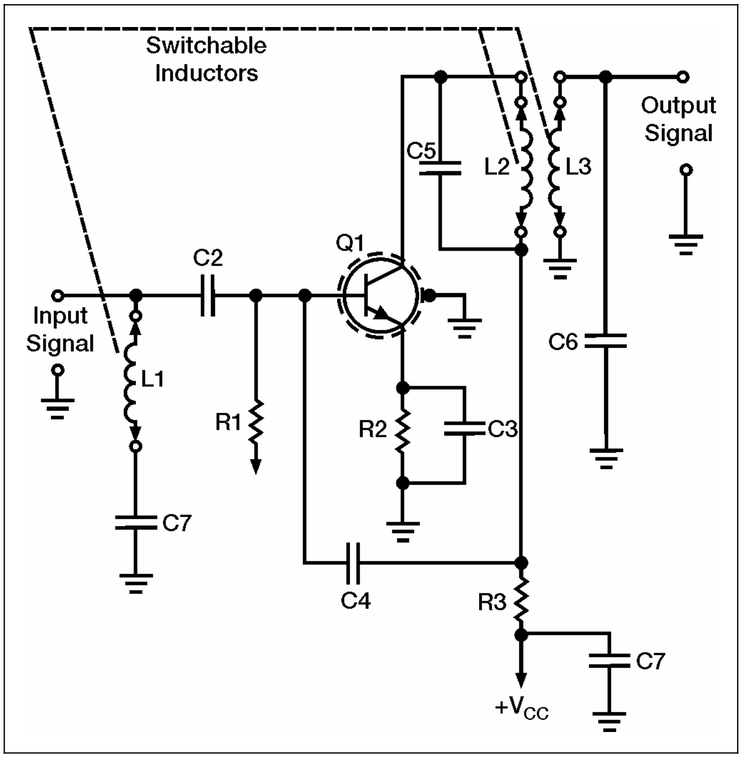
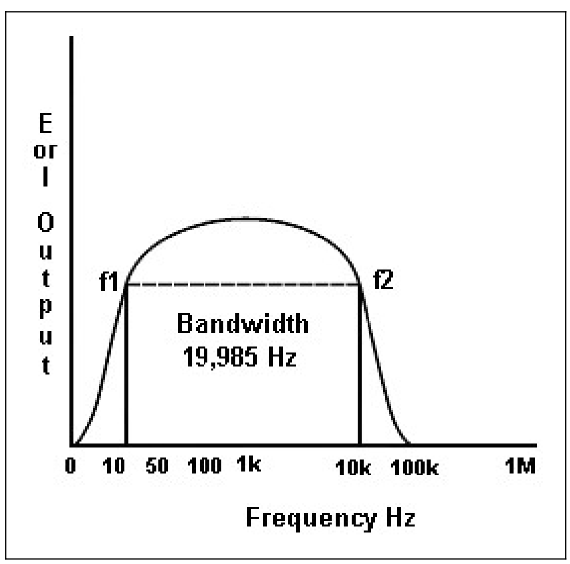


Figure 6-19. Typical RF Amplifier for VHF Television Receiver

SUMMARY

6-77. Now that we have completed this chapter, the following is a short review of the more important points. Answer the check-on-learning questions, found after the summary, to determine how much you have learned from this chapter.

FREQUENCY-RESPONSE CURVE - enables you to determine the BANDWIDTH and the UPPER and LOWER FREQUENCY LIMITS of an amplifier.



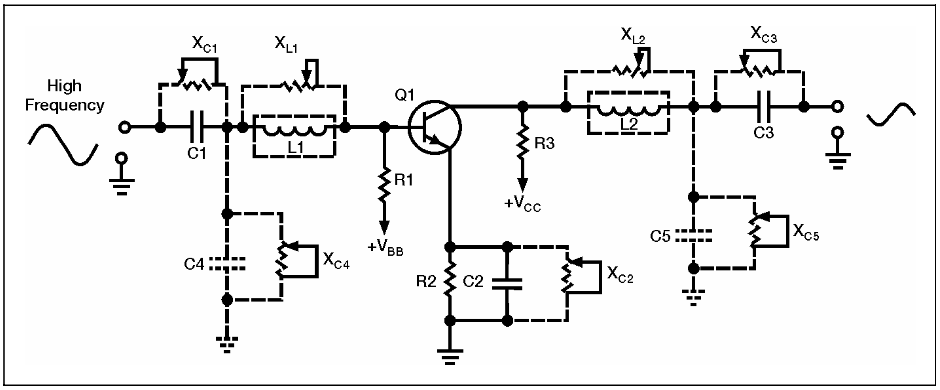
The BANDWIDTH of an amplifier is determined by the following formula:

$BW = f_2 - f_1$

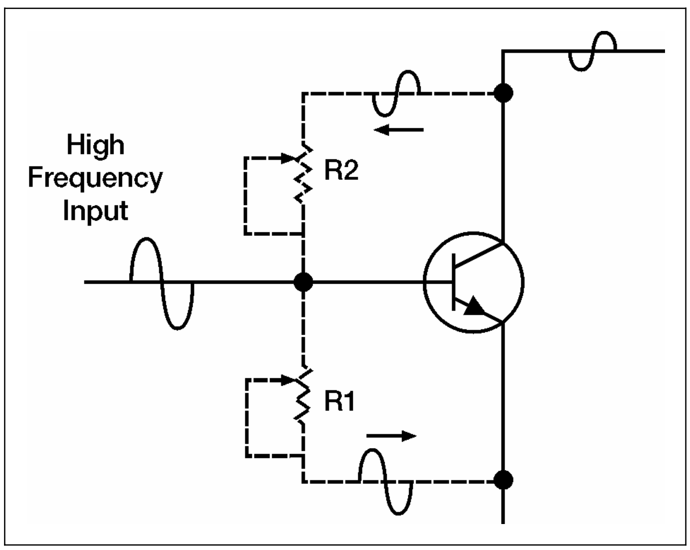
Where:

BW is the bandwidth. F_2 is the upper-frequency limit, and f_1 is the lower-frequency limit.

UPPER-FREQUENCY RESPONSE - this response of an amplifier is limited by the inductance and capacitance of the circuit.



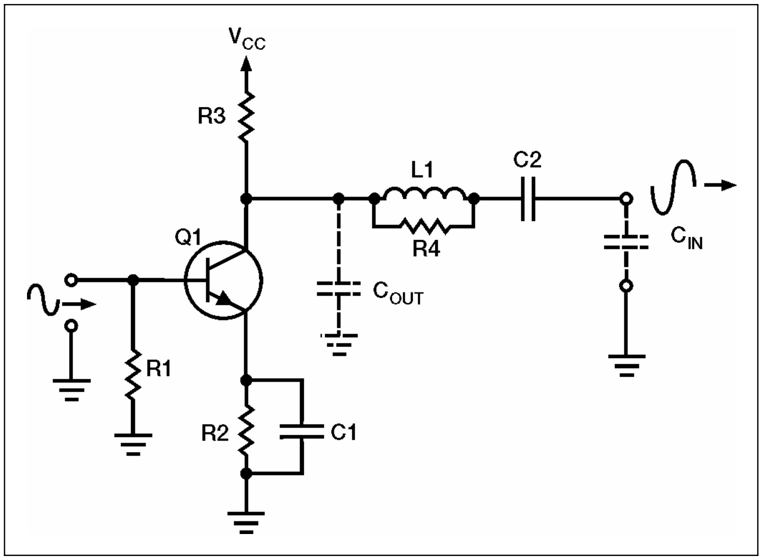
INTERELECTRODE CAPACITANCE - from a transistor causes DEGENERATIVE FEEDBACK at high frequencies.



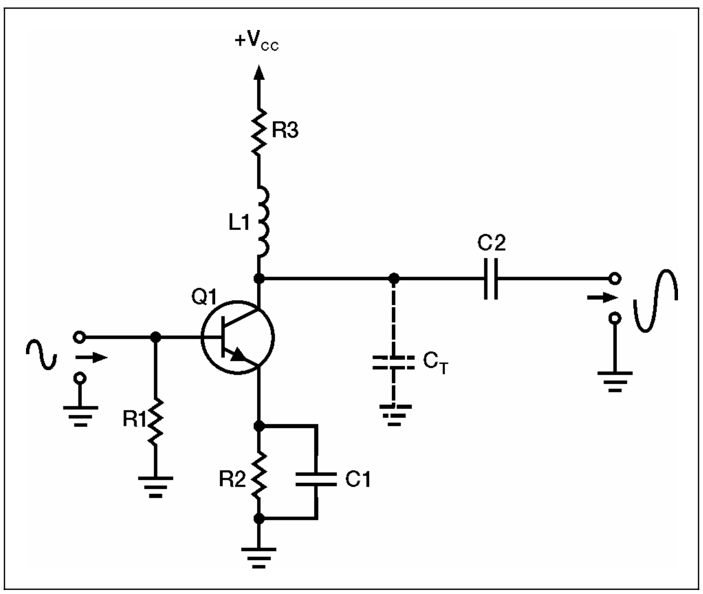
VIDEO AMPLIFIERS - must have a frequency response of 10 Hz to 6 MHZ. To provide this frequency response, both high- and low-frequency compensation must be used.

PEAKING COILS - used in video amplifiers to overcome the high-frequency limitations caused by the capacitance of the circuit.

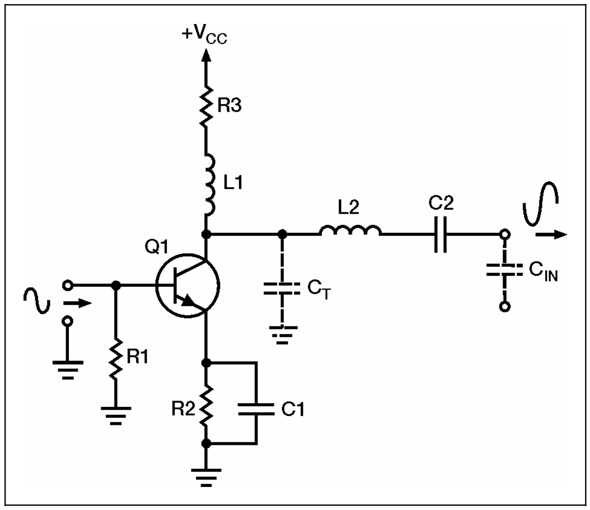
SERIES PEAKING - accomplished by a peaking coil in series with the output-signal path.



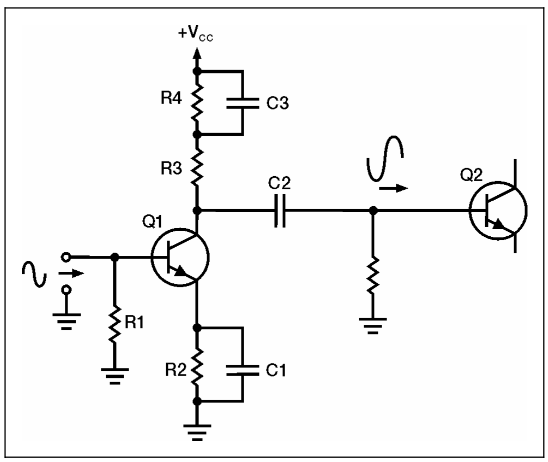
SHUNT PEAKING - accomplished by a peaking coil in parallel (shunt) with the output-signal path.



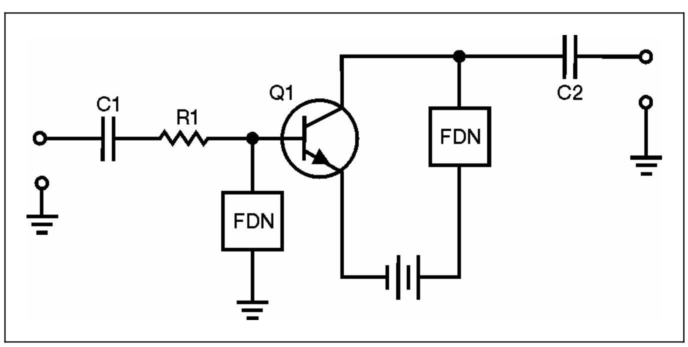
COMBINATION PEAKING - accomplished by using both series and shunt peaking.



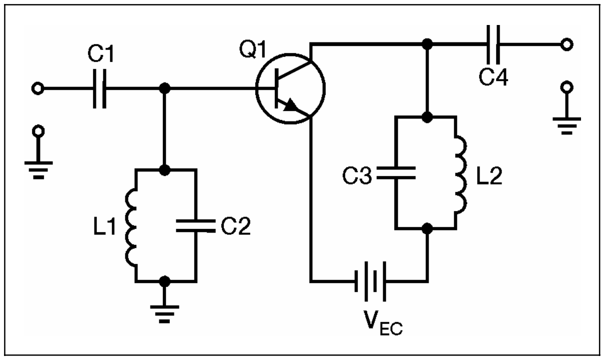
LOW-FREQUENCY COMPENSATION - accomplished in a video amplifier by the use of a parallel RC circuit in series with the load resistor.



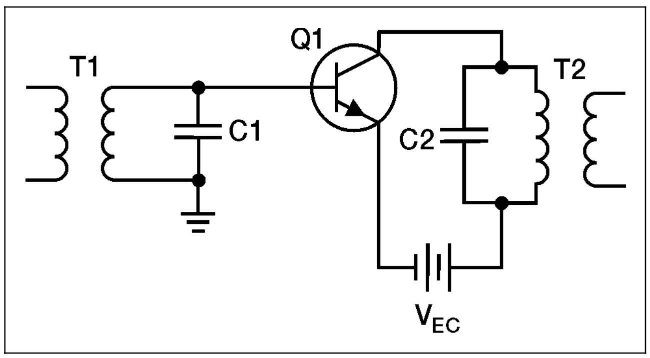
RADIO FREQUENCY AMPLIFIER - uses FREQUENCY-DETERMINING NETWORKS to provide the required response at a given frequency.



FREQUENCY-DETERMINING NETWORK - an RF amplifier provides maximum impedance at the desired frequency. It is a parallel LC circuit that is called a TUNED CIRCUIT.

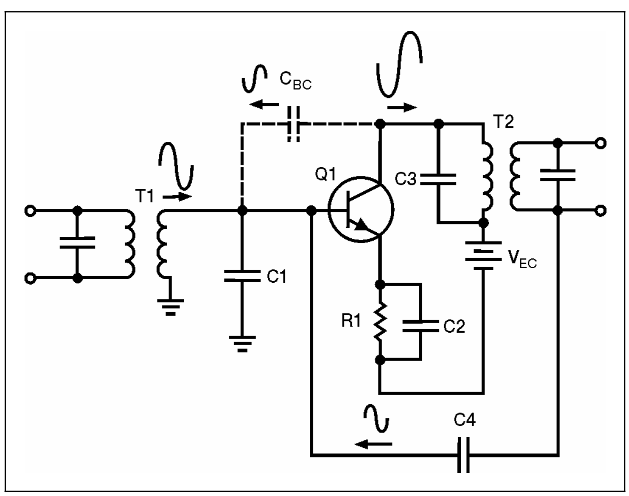


TRANSFORMER COULING - the most common form of coupling in RF amplifier. This coupling is accomplished by the use of RF transformers as part of the frequency determining network for the amplifier.



ADEQUATE BANDPASS - accomplished by optimum coupling in the RF transformer or by the use of a swamping resistor.

NEUTRALIZATION – in an RF amplifier provides feedback (usually positive) to overcome the effects caused by the base-to-collector interelectrode capacitance.



CHAPTER 6
CHECK-ON-LEARNING QUESTIONS

When you are satisfied that you have answered every question to the best of your ability, check your answers using Appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. RF amplifiers are used to amplify signals between what range?

2. The frequency-response curve provides a picture of what?

3. What does the shape of the frequency-response curve represent?

4. What is the bandwidth of an amplifier?

5. What are the upper and lower frequency limits of an amplifier?

6. What do you use to calculate true power?

7. What are the factors that limit the frequency response of a transistor amplifier?

8. There should be no limits to the frequency response if the amplifier circuit is made up of only what?

9. What type of feedback is usually caused by interelectrode capacitance?

10. What is the major factor that limits the high-frequency response of an amplifier circuit?

11. What happens to capacitive reactance as frequency increases?

12. What happens to inductive reactance as frequency increases?

13. What components can be used to increase the high-frequency response of an amplifier?

14. What is the definition of series peaking?

15. What do you call the technique when a coil is placed in parallel with the output signal path?

16. What is it called when you use series peaking and shunt peaking together?

17. What component in an amplifier circuit tends to limit the low-frequency response of the amplifier?

18. What do you use to calculate the gain of a stage?

19. What do you use to calculate voltage gain?

20. What happens to the input signal to the transistor when R2 is increased in value in a simple amplifier circuit?

21. What is a frequency-determining network?

22. What do you call the circuit when the parallel LC is used as a frequency-determining network?

23. What do you use, in most cases, to change capacitance?

24. Why would you use a swamping resistor?

25. For transformers, to what does coupling refer?

26. What type of coupling will usually provide the necessary bandpass for the frequency-determining network?

27. What is the name of the process that overcomes the problems of high frequencies in RF amplifiers?

28. What causes hysteresis loss?

29. Where could the energy be going if it was not going into hysteresis loss?

30. What process do you use to solve the problem of interelectrode capacitance in the transistor of an RF amplifier?

31. What do you use to neutralize unwanted degenerative feedback?

32. What type of feedback is usually caused by the base-to-collector interelectrode capacitance?

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Chapter 7

Special Amplifiers

LEARNING OBJECTIVES

Learning objectives serve as a preview of the information you are expected to learn in this chapter. The comprehensive check-on-learning questions, found at the end of the chapter, are based on the objectives. Upon completion of this chapter, you will be able to perform the following learning objectives:

- Describe the basic operation of a differential amplifier.
- Describe the operation of a differential amplifier under the following conditions:
- Single-input, single-output.
- Single-input, differential-output.
- Differential-input, differential-output.
- List the characteristics of an operational amplifier.
- Identify the symbol for an operational amplifier.
- Label the blocks on a block diagram of an operational amplifier.
- Describe the operation of an operational amplifier with inverting and noninverting configurations.
- Describe the bandwidth of a typical operational amplifier and methods to modify the bandwidth.
- Identify the following applications of operational amplifiers:
- Adder.
- Subtractor.
- State the common usage for a magnetic amplifier.
- Describe the basic operation of a magnetic amplifier.
- Describe various methods of changing inductance.
- Identify the purpose of components in a simple magnetic amplifier.

INTRODUCTION TO SPECIAL AMPLIFIERS

7-1. So far this TC has covered a great amount of information about amplifiers. You have learned about amplification and how the different classes of amplifiers affect amplification. You have also learned about the many factors that must be considered when working with amplifiers (such as impedance, feedback, frequency response, and coupling). However, this TC has only “scratched the surface” of the study of amplifiers. There is still much more to learn about amplifiers.

7-2. As in chapter 6, the circuits shown in this chapter are intended to present particular concepts to you. Therefore, the circuits may be incomplete or not practical for use in an actual piece of electronic equipment. Remember that the text is intended to teach certain facts about amplifiers, and in order to simplify the illustrations used, complete operational circuits are not always shown.

7-3. This chapter discusses the following three types of special amplifiers:

- Differential amplifiers.
- Operational amplifiers.
- Magnetic amplifiers.

These are called special amplifiers because they are used only in certain types of equipment. The names of each of these special amplifiers describe the operation of the amplifier, not what is amplified.

7-4. A differential amplifier is an amplifier that can have two input signals and/or two output signals. This amplifier can amplify the difference between two input signals. Differential amplifiers can also "cancel out" common signals at the two inputs.

7-5. One of the more interesting aspects of an operational amplifier is that it can be used to perform mathematical operations electronically. Properly connected, an operational amplifier can add, subtract, multiply, divide, and even perform the calculus operations of integration and differentiation. These amplifiers were originally used in a type of computer known as the "analog computer" but are now used in many electronic applications.

7-6. A magnetic amplifier does not amplify magnetism but uses magnetic effects to produce amplification of an electronic signal. The magnetic amplifier uses a device called a "saturable-core reactor" to control an AC output signal. The primary use of magnetic amplifiers is in power control systems.

7-7. These brief descriptions of the three special amplifiers are intended to provide you with a general idea of what these amplifiers are and how they can be used. The rest of this chapter will provide you with more detailed information about these special amplifiers.

DIFFERENTIAL AMPLIFIERS

7-8. A differential amplifier has two possible inputs and two possible outputs. This arrangement means that the differential amplifier can be used in a variety of ways. Before examining the three basic configurations that are possible with a differential amplifier, you need to be familiar with the basic circuitry of a differential amplifier.

BASIC DIFFERENTIAL AMPLIFIER CIRCUIT

7-9. Before you are shown the operation of a differential amplifier, you will be shown how a simpler circuit works. This simpler circuit, known as the difference amplifier, has one thing in common with the differential amplifier and that is that it operates on the difference between two inputs. However, the difference amplifier has only one output while the differential amplifier can have two outputs.

7-10. You should be familiar with some amplifier circuits, which should give you an idea of what a difference amplifier is like. Figure 7-1 shows two of the basic configurations for transistor amplifiers (the CE and the CB).

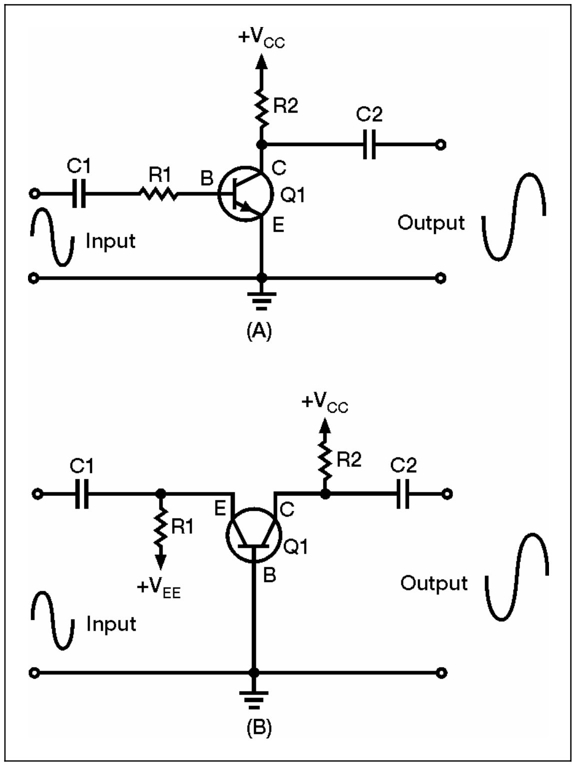


Figure 7-1. Common Emitter and Common Base Amplifiers

7-11. Figure 7-1, view (A) shows a CE amplifier. The output signal is an amplified version of the input signal and is 180 degrees out of phase with the input signal. View (B) is a CB amplifier. In this circuit, the output signal is an amplified version of the input signal and is in phase with the input signal. In both of these circuits, the output signal is controlled by the base-to-emitter bias. As this bias changes (because of the input signal) the current through the transistor changes. This causes the output signal developed across the collector load (R2) to change. None of this information is new; this is just a review of what you have already been shown regarding transistor amplifiers.

NOTE: Bias arrangements for the following explanations will be termed base-to-emitter. In other publications you will see the term emitter-to-base used to describe the same bias arrangement.

THE TWO-INPUT, SINGLE-OUTPUT, DIFFERENCE AMPLIFIER

7-12. If you combine the CB and CE configurations into a single transistor amplifier, you will have a circuit like the one shown in Figure 7-2. This circuit is the two-input, single-output, difference amplifier.

7-13. The transistor shown in Figure 7-2 has two inputs (the emitter and the base) and one output (the collector). Remember that the current through the transistor, and therefore the output signal, is controlled by the base-to-emitter bias. In the circuit, the combination of the two input signals controls the output signal. In fact, the difference between the input signals determines the base-to-emitter bias.

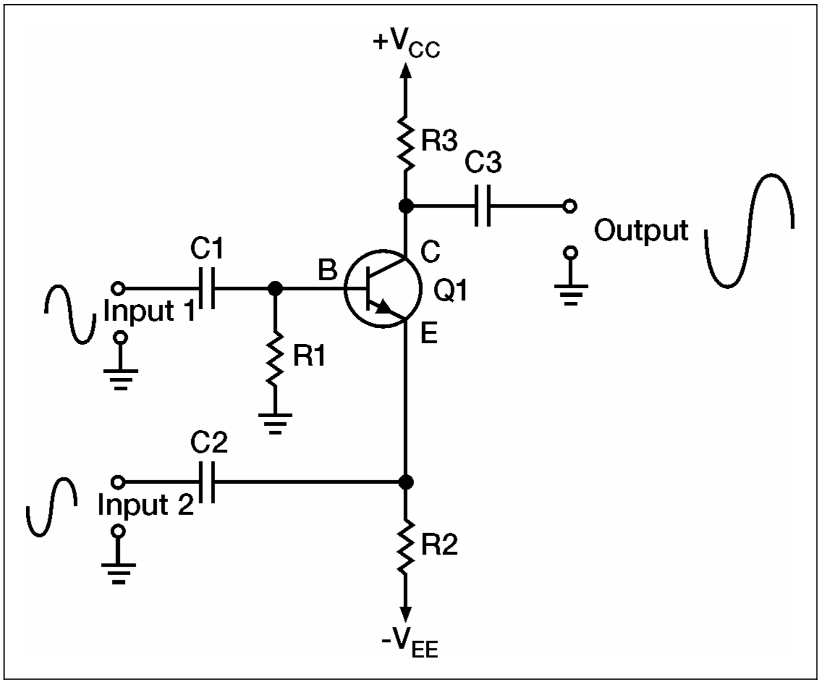


Figure 7-2. Two-input, Single-output, Difference Amplifier

7-14. For the purpose of examining the operation of the circuit in Figure 7-2, assume that the circuit has a gain of -10. This means that for each 1-volt change in the base-to-emitter bias, there would be a 10-volt change in the output signal. Also assume that the input signals will peak at 1-volt levels (+1 volt for the positive peak and -1 volt for the negative peak). The secret to understanding this circuit (or any transistor amplifier circuit) is to realize that the collector current is controlled by the base-to-emitter bias. In other words, in this circuit the output signal (the voltage developed across R3) is determined by the difference between the voltage on the base and the voltage on the emitter.

7-15. Figure 7-3 shows this two-input, single-output amplifier with input signals that are equal in amplitude and 180 degrees out of phase. Input number 1 has a positive alternation when input number 2 has a negative alternation and vice versa.

7-16. The circuit and the input and output signals are shown at the top of the figure. The lower portion of the figure is a comparison of the input signals and the output signal. Notice the vertical lines marked “T0” through “T8.” These represent “time zero” through “time eight.” In other words, these lines provide a way to examine the two input signals and the output signal at various instants of time.

7-17. In Figure 7-3 at time zero (T0) both input signals are at 0 volts. The output signal is also at 0 volts. Between time zero (T0) and time one (T1), input signal number 1 goes positive and input signal number 2 goes negative. Each of these voltage changes causes an increase in the base-to-emitter bias, which causes current through Ql to increase. Increased current through Q1 results in a greater voltage drop across the collector load (R3) that causes the output signal to go negative.

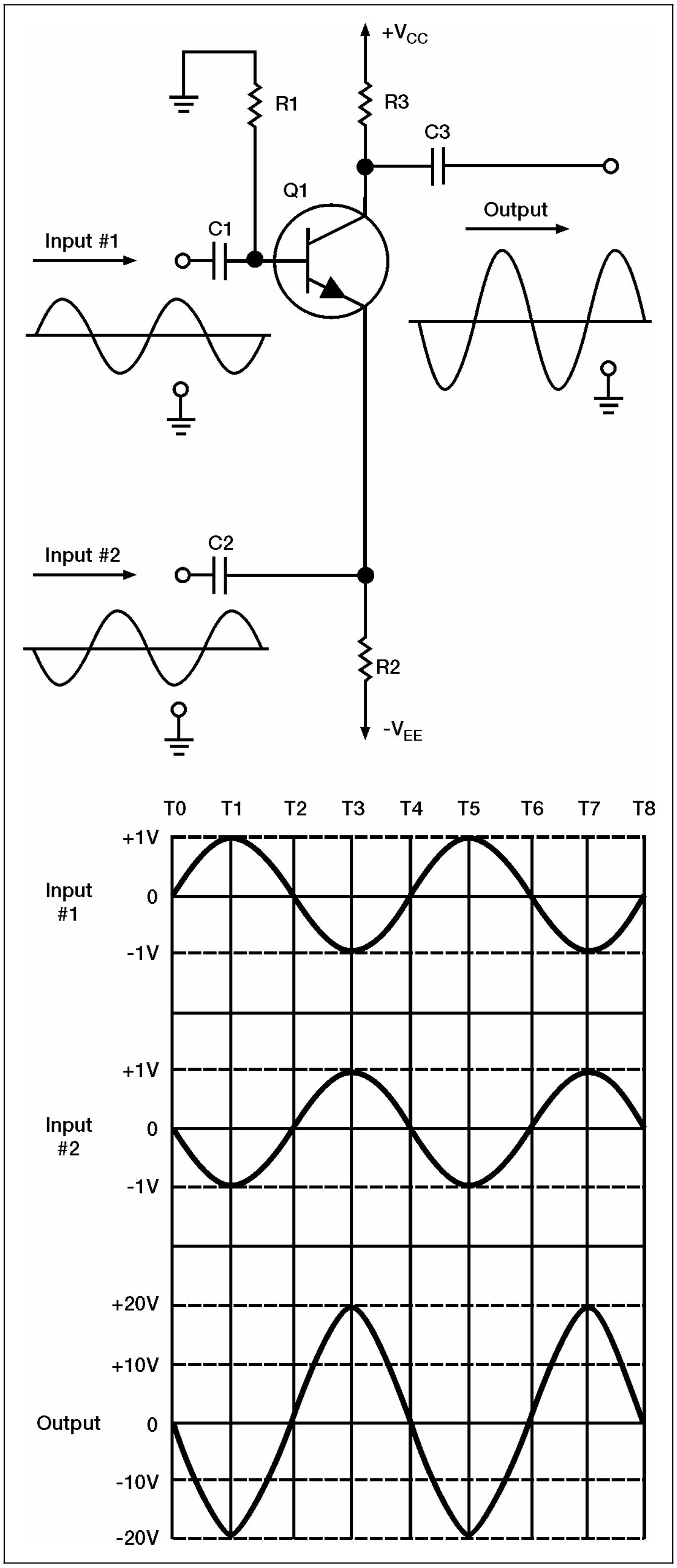


Figure 7-3. Input Signals 180° Out of Phase

7-18. By time one (T1), input signal number 1 has reached +1 volt and input signal number 2 has reached -1 volt. This is an overall increase in base-to-emitter bias of 2 volts. Since the gain of the circuit is -10, the output signal has decreased by 20 volts. As you can see, the output signal has been determined by the difference between the two input signals. In fact, the base-to-emitter bias can be found by subtracting the value of input signal number 2 from the value of input signal number 1 (compute this by using the following equation):

Bias = (input signal #2) - (input signal #1)

Bias = (+1 V) – (-1 V)

Bias = +1 V + 1 V

Bias = +2 V

7-19. Between time one (T1) and time two (T2), input signal number 1 goes from +1 volt to 0 volts and input signal number 2 goes from -1 volt to 0 volts. At time two (T2) both input signals are at 0 volts and the base-to-emitter bias has returned to 0 volts. The output signal is also 0 volts (compute this by using the following equation):

Bias = (input signal #1) - (input signal #2)

Bias = (0 V) - (0 V)

Bias = 0 V

7-20. Between time two (T2) and time three (T3), input signal number 1 goes negative and input signal number 2 goes positive. At time three (T3), the value of the base-to-emitter bias is -2 volts (compute this by using the following equation):

Bias = (input signal #1) - (input signal #2)

Bias = (-1 V) – (+1 V)

Bias = (-1 V) + (-1 V)

Bias = -2 V

NOTE: This causes the output signal to be +20 volts at time three (T3).

7-21. Between time three (T3) and time four (T4), input signal number 1 goes from -1 volt to 0 volts and input signal number 2 goes from +1 volt to 0 volts. At time four (T4) both input signals are 0 volts, the bias is 0 volts, and the output is 0 volts.

7-22. During time four (T4) through time eight (T8), the circuit repeats the sequence of events that took place from time zero (T0) through time four (T4). You can see that when the input signals are equal in amplitude and 180 degrees out of phase, the output signal is twice as large (40 volts peak to peak) as it would be from either input signal alone (if the other input signal were held at 0 volts). Figure 7-4 shows the two-input, single-output, difference amplifier with two input signals that are equal in amplitude and in phase.

7-23. Notice that the output signal remains at 0 volts for the entire time (T0 through T8). Since the two input signals are equal in amplitude and in phase, the difference between them (the base-to-emitter bias) is always 0 volts. This causes a 0-volt output signal.

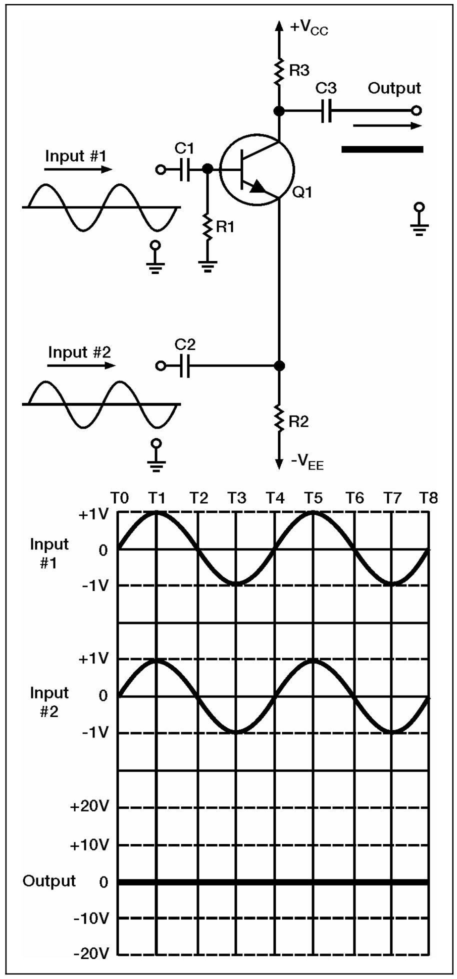


Figure 7-4. Input Signals in Phase

7-24. If you compute the bias at any time period (T0 through T8), you will see that the output of the circuit remains at a constant zero. For example:

Bias = (input signal #1) - (input signal #2)

T1 Bias = (+V) - (+1 V) = 0 V and so forth.

7-25. From the above example, you can see that when the input signals are equal in amplitude and in phase, there is no output from the difference amplifier because there is no difference between the two inputs. You also know that when the input signals are equal in amplitude but 180 degrees out of phase, the output looks just like the input except for amplitude and a 180-degree phase reversal with respect to input signal number 1. If the input signals are equal in amplitude but different in phase by something other than 180 degrees, then that would mean the following:

- Sometimes one signal would be going negative while the other would be going positive.
- Sometimes both signals would be going positive.
- Sometimes both signals would be going negative.

In this instance, the output signal will not look like the input signals because Figure 7-5 shows a difference amplifier with two input signals that are equal in amplitude but 90 degrees out of phase. From the figure you can see that at time zero (T0) input number one is at 0 volts and input number 2 is at -1 volt. The base-to-emitter bias is found to be +1 volt. This +1 volt bias signal causes the output signal to be -10 volts at time zero (T0). Between time zero (T0) and time one (T1), both input signals go positive. The difference between the input signals stays constant. The effect of this is to keep the bias at +1 volt for the entire time between T0 and T1. This, in turn, keeps the output signal at -10 volts.

7-26. Between time one (T1) and time two (T2), input signal number one goes in a negative direction but input signal number two continues to go positive. Now the difference between the input signals decreases rapidly from +1 volt. Halfway between T1 and T2 (the dotted vertical line), input signal number one and input signal number two are equal in amplitude. The difference between the input signals is 0 volts and this causes the output signal to be 0 volts. From this point to T2 the difference between the input signals is a negative value. At T2 you can compute the following:

Bias = (input signal #1) - (input signal #2)

Bias = (0 V) - (+1 V)

Bias = 1 V

7-27. From time two (T2) to time three (T3), input signal number 1 goes negative and input signal number 2 goes to zero. The difference between them stays constant at -1 volt. Therefore, the output signal stays at a +10-volt level for the entire time period from T2 to T3. When computing at T3 the bias condition will be:

Bias = (input signal #1) - (input signal #2)

Bias = (-1 V) - (0 V)

Bias = -1 V

7-28. Between T3 and T4 input signal number 1 goes to zero while input signal number 2 goes negative. This again causes a rapid change in the difference between the input signals. Halfway between T3 and T4 (the dotted vertical line) the two input signals are equal in amplitude. Therefore, the difference between the input signals is 0 volts, and the output signal becomes 0 volts. From that point to T4, the difference between the input signals becomes a positive voltage. When computing at T4 the bias condition will be:

Bias = (input signal #1) - (input signal #2)

Bias = (0 V) - (-1 V)

Bias = +1 V

NOTE: The sequence of events from T4 toT8 is the same as those of T0 to T4.

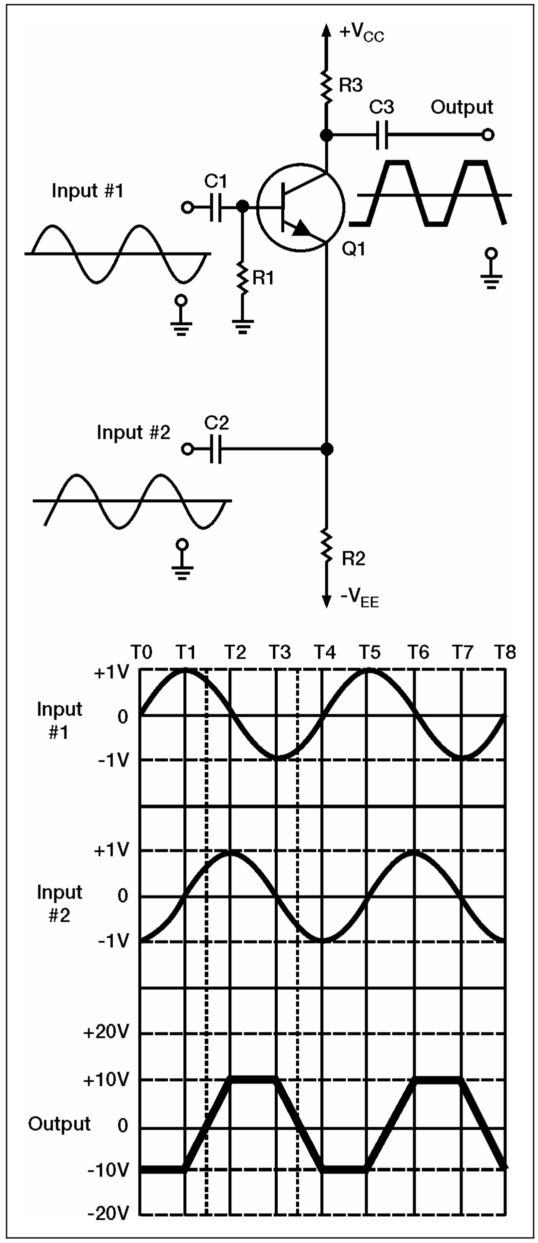


Figure 7-5. Input Signals 90° Out of Phase

7-29. As you have seen, this amplifier amplifies the difference between two input signals. However, this is not a differential amplifier. A differential amplifier has two inputs and two outputs. The circuit you have just been shown has only one output. We will now look at a typical differential amplifier.

TYPICAL DIFFERENTIAL AMPLIFIER CIRCUIT

7-30. Figure 7-6 shows the schematic of a typical differential amplifier. This circuit requires two transistors to provide the two inputs and two outputs. If you look at one input and the transistor with which it is associated, you will see that each transistor is a CE amplifier for that input (input 1 and Q1; input 2 and Q2). R1 develops the signal at input 1 for Q1 and R5 develops the signal at input 2 for Q2. R3 is the emitter resistor for both Q1 and Q2. Notice that R3 is NOT bypassed. This means that when a signal at input 1 affects the current through Q1, that signal is developed by R3. The current through Q1 must flow through R3. As this current changes, the voltage developed across R3 changes. When a signal is developed by R3, it is applied to the emitter of Q2. In the same way signals at input 2 affect the current of Q2, are developed by R3, and are felt on the emitter of Q1. R2 develops the signal for output 1 and R4 develops the signal for output 2.

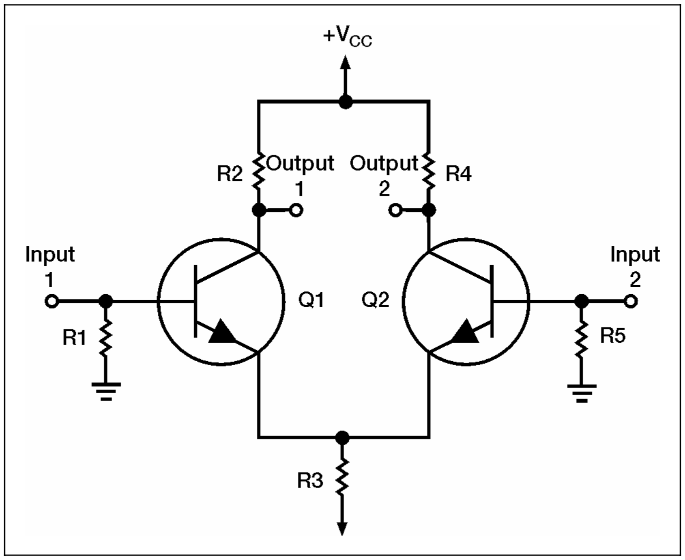


Figure 7-6. Differential Amplifier

7-31. Even though this circuit is designed to have two inputs and two outputs, it is not necessary to use both inputs and both outputs. Remember, a differential amplifier was defined as having two possible inputs and two possible outputs. A differential amplifier can be connected as a single-input; single-output device; a single-input, differential-output device; or a differential-input, differential-output device.

SINGLE-INPUT, SINGLE-OUTPUT, DIFFERENTIAL AMPLIFIER

7-32. Figure 7-7 shows a differential amplifier with one input (the base of Q1) and the output (the collector of Q2). The second input (the base of Q2) is grounded and the second output (the collector of Q1) is not used.

7-33. When the input signal developed by R1 goes positive, the current through Q1 increases. This increased current causes a positive-going signal at the top of R3. This signal is felt on the emitter of Q2. Since the base of Q2 is grounded, the current through Q2 decreases with a positive-going signal on the emitter. This decreased current causes less voltage drop across R4. Therefore, the voltage at the bottom of R4 increases and a positive-going signal is felt at the output.

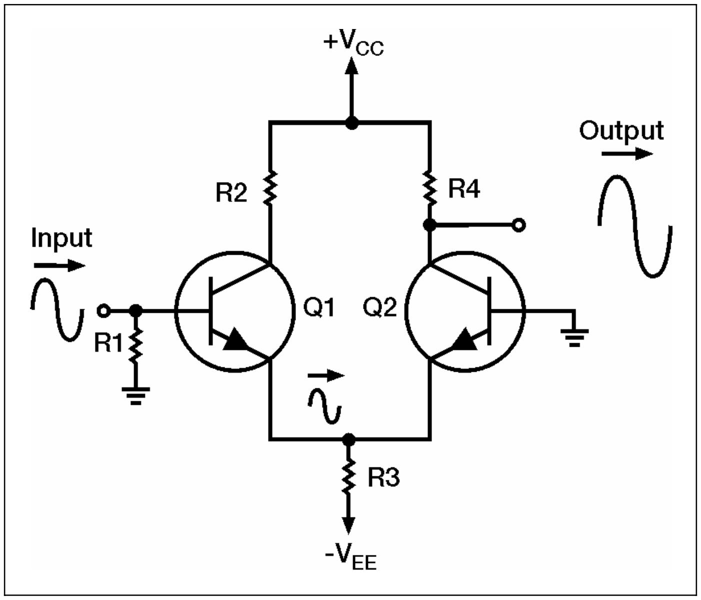


Figure 7-7. Single-input, Single-output Differential Amplifier

7-34. When the input signal developed by R1 goes negative, the current through Q1 decreases. This decreased current causes a negative-going signal at the top of R3. This signal is felt on the emitter of Q2. When the emitter of Q2 goes negative, the current through Q2 increases. This increased current causes more of a voltage drop across R4. Therefore, the voltage at the bottom of R4 decreases and a negative-going signal is felt at the output.

7-35. This single-input, single-output, differential amplifier is very similar to a single-transistor amplifier as far as input and output signals are concerned. This use of a differential amplifier does provide amplification of AC or DC signals but does not take full advantage of the characteristics of a differential amplifier.

SINGLE-INPUT, DIFFERENTIAL-OUTPUT, DIFFERENTIAL AMPLIFIER

7-36. In chapter 5 you were shown several phase splitters. Remember that a phase splitter provides two outputs from a single input. These two outputs are 180 degrees out of phase with each other. The single-input, differential-output, differential amplifier will do the same thing.

7-37. Figure 7-8 shows a differential amplifier with one input (the base of Q1) and two outputs (the collectors of Q1 and Q2). One output is in phase with the input signal and the other output is 180 degrees out of phase with the input signal. The outputs are differential outputs.

7-38. The input signal is developed by R1. As the current through Q1 varies with the input signal, the voltage at the top of R3 will vary with the input signal. This causes a signal to be felt on the emitter of Q2. This signal on the emitter of Q2 causes the current to vary (180 degrees out of phase with the input signal) through Q2. The variations of current in Q1 and Q2 are developed by R2 and R4, respectively, as output number one and output number two.

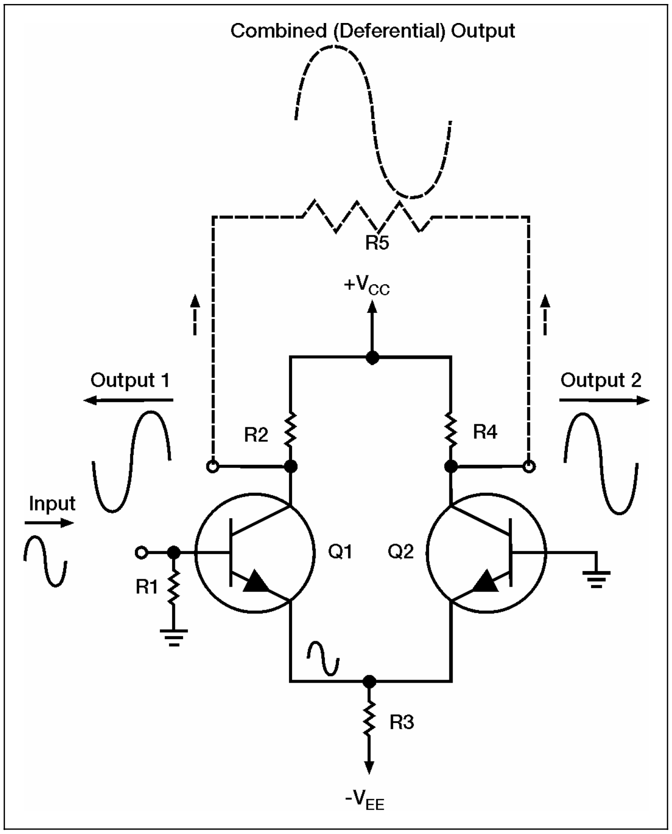


Figure 7-8. Single-input, Differential-output Differential Amplifier

7-39. Now you know how a differential amplifier can produce two amplified differential output signals from a single input signal. Another point about this configuration is that if a combined output signal is taken between outputs number 1 and 2, this single output will be twice the amplitude of the individual outputs. In other words, you can double the gain of the differential amplifier (single-output) by taking the output signal between the two output terminals. This single-output signal will be in phase with the input signal. This is shown by the phantom signal above R5 (the phantom resistor connected between outputs number 1 and 2 would be used to develop this signal).

DIFFERENTIAL-INPUT, DIFFERENTIAL-OUTPUT, DIFFERENTIAL AMPLIFIER

7-40. When a differential amplifier is connected with a differential input and a differential output, the full potential of the circuit is used. Figure 7-9 shows a differential amplifier with this type of configuration (differential-input, differential-output). This configuration normally uses two input signals that are 180 degrees out of phase. This causes the difference (differential) signal to be twice as large as either input alone. This is just like the two-input, single-output difference amplifier with input signals that are 180 degrees out of phase.

7-41. Output number 1 is a signal that is in phase with input number 2, and output number 2 is a signal that is in phase with input number 1. The amplitude of each output signal is the input signal multiplied by the gain of the amplifier. With 180-degree out-of-phase input signals, each output signal is greater in amplitude than either input signal by a factor of the gain of the amplifier.

7-42. When an output signal is taken between the two output terminals of the amplifier (as shown by the phantom connections, resistor, and signal), the combined output signal is twice as great in amplitude as either signal at output number 1 or output number 2. This is because output number 1 and output number 2 are 180 degrees out of phase with each other. When the input signals are 180 degrees out of phase, the amplitude of the combined output signal is equal to the amplitude of one input signal multiplied by two times the gain of the amplifier.

7-43. When the input signals are not 180 degrees out of phase, the combined output signal taken across output one and output two is similar to the output that you were shown for the two-input, single-output, difference amplifier. The differential amplifier can have two outputs (180 degrees out of phase with each other), or the outputs can be combined as shown in Figure 7-9.

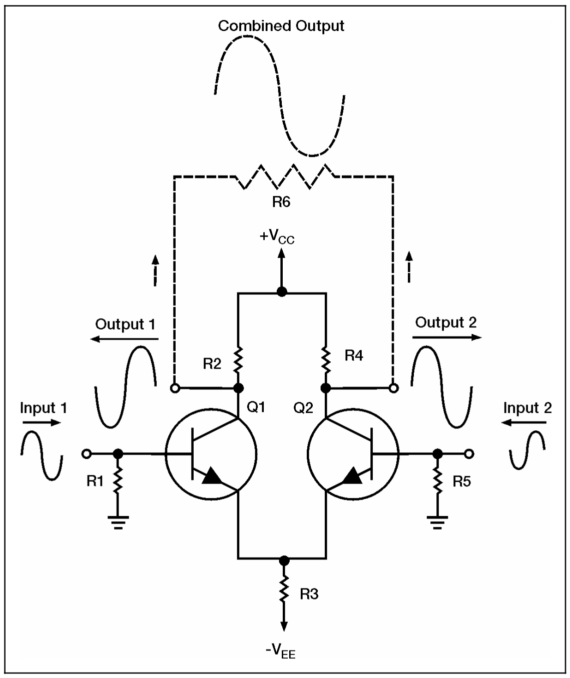


Figure 7-9. Differential-input, Differential-output Differential Amplifier

OPERATIONAL AMPLIFIERS

7-44. An operational amplifier is designed to be used with other circuit components to perform either computing functions (addition and/or subtraction) or some type of transfer operation (such as filtering). Operational amplifiers are usually high-gain amplifiers with the amount of gain determined by feedback.

7-45. Operational amplifiers have been in use for some time. They were originally developed for analog (non-digital) computers and used to perform mathematical functions. Operational amplifiers were not often used in other devices because they were expensive and more complicated than other circuits.

7-46. Today many devices use operational amplifiers. Operational amplifiers are used as DC amplifiers, AC amplifiers, comparators, oscillators, filter circuits, and many other applications. The reason for this widespread use of the operational amplifier is that it is a very versatile and efficient device. As an IC (chip), the operational amplifier has become

an inexpensive and readily available “building block” for many devices. In fact, an operational amplifier in IC form is no more expensive than a good transistor.

CHARACTERISTICS OF AN OPERATIONAL AMPLIFIER

7-47. Figure 7-10 shows the schematic symbols for an operational amplifier. View (A) shows the power supply requirements and view (B) shows only the input and output terminals. An operational amplifier is a special type of high-gain, DC amplifier. To be classified as an operational amplifier, the circuit must have certain characteristics. The three most important characteristics of an operational amplifier are:

- Very high gain.
- Very high input impedance.
- Very low output impedance.

7-48. Since no single amplifier stage can provide all these characteristics well enough to be considered an operational amplifier, various amplifier stages are connected together. The total circuit made up of these individual stages is called an operational amplifier. This circuit (the operational amplifier) can be made up of individual components (such as transistors, resistors, capacitors, and so forth). However, the most common form of the operational amplifier is an IC. The IC (chip) will contain the various stages of the operational amplifier and can be treated and used as if it were a single stage.

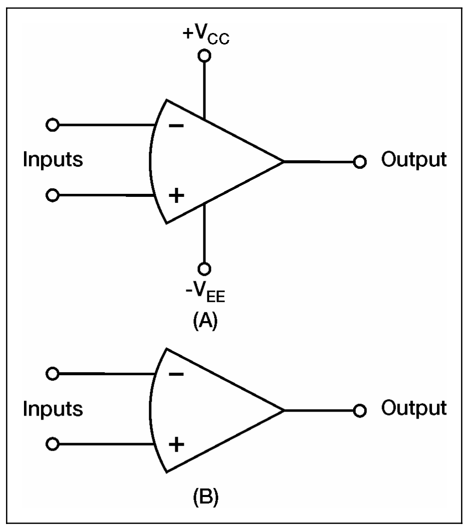


Figure 7-10. Schematic Symbols of an Operational Amplifier

BLOCK DIAGRAM OF AN OPERATIONAL AMPLIFIER

7-49. Figure 7-11 is a block diagram of an operational amplifier. Notice that there are three stages (differential amplifier, voltage amplifier, and output amplifier) within the operational amplifier.

7-50. The first stage (also known as the input stage) is a differential amplifier. As an input stage, the differential amplifier provides differential inputs and a frequency response down to DC. Special techniques are used to provide the high input impedance necessary for the operational amplifier.

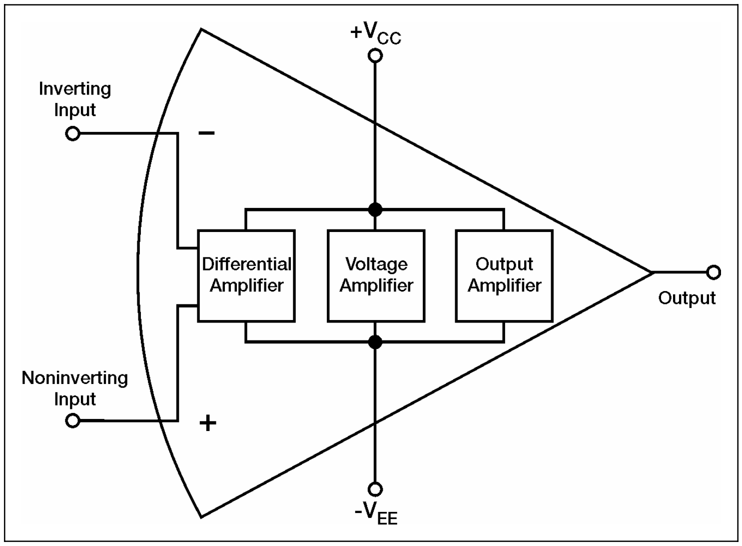


Figure 7-11. Block Diagram of an Operational Amplifier

7-51. The second stage is a high-gain voltage amplifier. This stage may be made from several transistors to provide high gain. A typical operational amplifier could have a voltage gain of 200, 000. Most of this gain comes from the voltage amplifier stage.

7-52. The final stage of the operational amplifier is an output amplifier. The output amplifier provides low output impedance. The actual circuit used could be an emitter follower. The output stage should allow the operational amplifier to deliver several milliamperes to a load.

7-53. Notice that the operational amplifier has a positive power supply (+V_{CC}) and a negative power supply (-V_{EE}). This arrangement enables the operational amplifier to produce either a positive or a negative output.

7-54. The two input terminals are labeled' 'inverting input” (-) and “noninverting input” (+). The operational amplifier can be used with three different input conditions (modes). With differential inputs (first mode), both input terminals are used and two input signals that are 180 degrees out of phase with each other are used. This produces an output signal that is in phase with the signal on the noninverting input. If the noninverting input is grounded and a signal is applied to the inverting input (second mode), the output signal will be 180 degrees out of phase with the input signal (and one-half the amplitude of the first mode output). If the inverting input is grounded and a signal is applied to the noninverting input (third mode), the output signal will be in phase with the input signal (and one-half the amplitude of the first mode output).

CLOSED-LOOP OPERATION OF AN OPERATIONAL AMPLIFIER

7-55. Operational amplifiers can have either a closed-loop operation or an open-loop operation. The operation (closed-loop or open-loop) is determined by whether or not feedback is used. Without feedback the operational amplifier has an open-loop operation. This open-loop operation is practical only when the operational amplifier is used as a comparator (a circuit which compares two input signals or compares an input signal to some fixed level of voltage). As an amplifier, the open-loop operation is not practical because the very high gain of the operational amplifier creates poor stability. Noise and

other unwanted signals are amplified so much in open-loop operation that the operational amplifier is usually not used in this way. Therefore, most operational amplifiers are used with feedback (closed-loop operation).

7-56. Operational amplifiers are used with degenerative (or negative) feedback that reduces the gain of the operational amplifier but greatly increases the stability of the circuit. In the closed-loop configuration, the output signal is applied back to one of the input terminals. This feedback is always degenerative (negative). In other words, the feedback signal always opposes the effects of the original input signal. One result of degenerative feedback is that the inverting and noninverting inputs to the operational amplifier will be kept at the same potential. Closed-loop circuits can be of the inverting configuration or noninverting configuration. However, the inverting configuration is used more often than the noninverting configuration.

Inverting Configuration

7-57. Figure 7-12 shows an operational amplifier in a closed-loop, inverting configuration. Resistor R2 is used to feed part of the output signal back to the input of the operational amplifier.

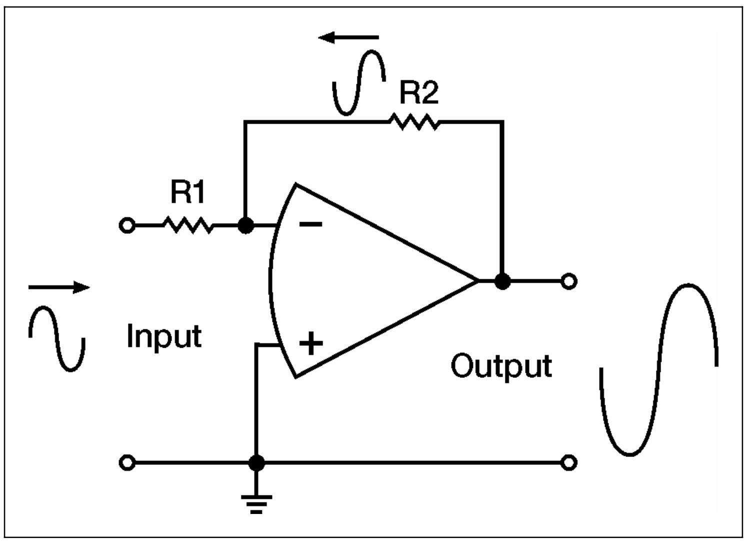


Figure 7-12. Inverting Configuration

7-58. It is important to remember the difference between the entire circuit (or operational circuit) and the operational amplifier. The operational amplifier is represented by the triangle-like symbol. The operational circuit includes the resistors and any other components, as well as the operational amplifier. In other words, the input to the circuit is shown in Figure 7-12. However, the signal at the inverting input of the operational amplifier is determined by the feedback signal as well as by the circuit input signal.

7-59. As you can see in Figure 7-12, the output signal is 180 degrees out of phase with the input signal. The feedback signal is a portion of the output signal and, therefore, also 180 degrees out of phase with the input signal. Whenever the input signal goes positive, the output signal and the feedback signal goes negative. The result of this is that the inverting input to the operational amplifier is always very close to 0 volts with this configuration. In fact, with the noninverting input grounded, the voltage at the inverting input to the operational amplifier is so small compared to other voltages in the circuit that it

is considered to be virtual ground. Remember, in a closed-loop operation the inverting and noninverting inputs are at the same potential.

7-60. Virtual ground is a point in a circuit that is at ground potential (0 volts) but is not connected to ground. Figure 7-13 shows an example of several circuits with points at virtual ground. In view (A), V1 (the left-hand battery) supplies +10 volts to the circuit while V2 (the right-hand battery) supplies -10 volts to the circuit. The total difference in potential in the circuit is 20 volts.

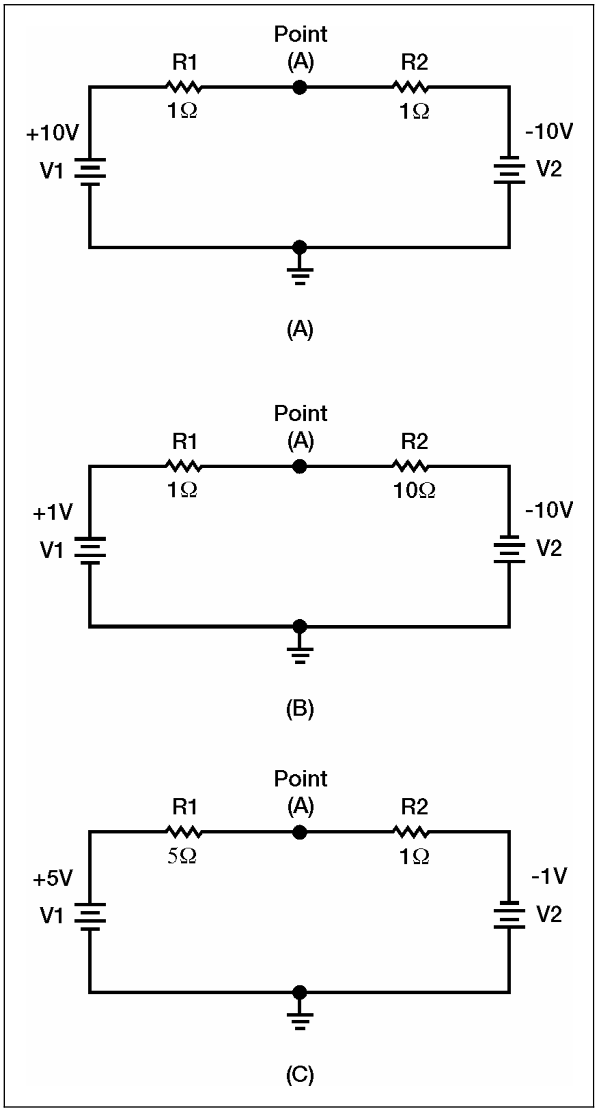


Figure 7-13. Virtual Ground Circuits

7-61. The total resistance of the circuit can be calculated as follows:

$$R_T = R1 + R2$$

$$R_T = 1\Omega + 1\Omega$$

$$R_T = 2\Omega$$

Now that the total resistance is known, the circuit current can be calculated as follows:

$$I_T = \frac{E_R}{R_T}$$

$$I_T = \frac{20 \text{ V}}{2 \ \Omega}$$

$$I_T = 10 \quad \text{A}$$

The voltage drop across R1can be computed as follows:

E_{R1} = R1 x I_T

E_{R1} = 1Ω X 10 A

E_{R1} = 10 V

The voltage at point A would be equal to the voltage of V1 minus the voltage drop of R1. Compute this as follows:

Voltage at point A = V1 - E_{R1}

Voltage at point A = +10 V- 10 V

Voltage at point A = 0 V

To check this result, compute the voltage drop across R2 and subtract this from the voltage at point A. The result should be the voltage of V2. Compute this as follows:

E_{R2} = R2 x I_T

E_{R2} = 1Ω x 10 A

E_{R2} = 10 V

V2 = (voltage at point A) - (E_{R2})

V2 = (0V) - (10 V)

V2 = -10 V

7-62. It is not necessary that the voltage supplied be equal to create a point of virtual ground. In Figure 7-13, view (B), V1 supplies +1 volt to the circuit while V2 supplies -10 volts. The total difference in potential is 11 volts. The total resistance of this circuit (R1 + R2) is 11 ohms. The total current (I_T) is 1 ampere. The voltage drop across R1 (E_{R1} = R1 x I_T) is 1 volt. The voltage drop across R2 (E_{R2} = R2 x I_T) is 10 volts. The voltage at point A can be computed as follows:

Voltage at point A = V1 - E_{R1}

Voltage at point A = (+1V) - (+1V)

Voltage at point A = 0 V

So point A is at virtual ground in this circuit also. To check the results, compute the voltage at V2 as follows:

$$V2 = (\text{voltage at point A}) - E_{R2}$$

$$V2 = (0\ V) - (+10\ V)$$

$$V2 = -10\ V$$

You can compute the values for view (C) and prove that point A in that circuit is also at virtual ground.

7-63. The whole point is that the inverting input to the operational amplifier shown in Figure 7-12 (for all practical purposes) is at virtual ground since it is at 0 volts. Since the inverting input is at 0 volts, there will be no current (for all practical purposes) flowing into the operational amplifier from the connection point of R1 and R2.

7-64. Given these conditions, the characteristics of this circuit are determined almost entirely by the values of R1 and R2. Figure 7-14 should help show how the values of R1 and R2 determine the circuit characteristics.

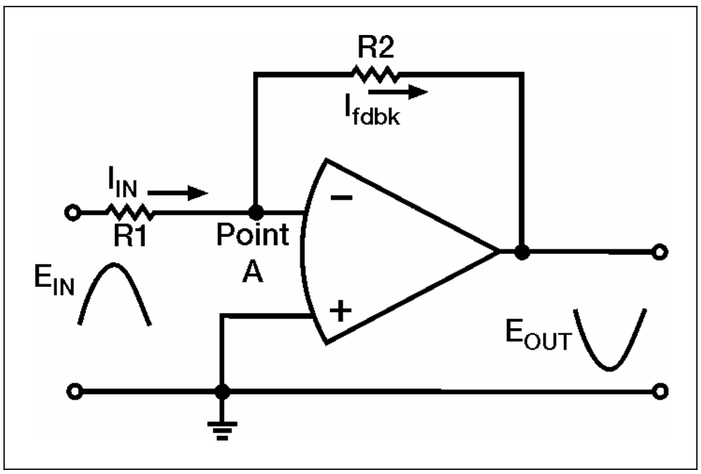


Figure 7-14. Current Flow in the Operational Circuit

NOTE: It should be stressed at this point that for purpose of explanation, the operational amplifier is a theoretically perfect amplifier. In actual practice we are dealing with less than perfect. In the practical operational amplifier there will be a slight input current with a resultant power loss. This small signal can be measured at the theoretical point of virtual ground. This does not indicate faulty operation.

7-65. As shown in Figure 7-14, the input signal causes current to flow through R1. Only the positive half cycle of the input signal is shown and will be discussed. Since the voltage at the inverting input of the operational amplifier is at 0 volts, the input current (I_{IN}) is computed by using the following formula:

$$I_{IN} = \frac{E_{IN}}{R1}$$

7-66. The output signal (which is opposite in phase to the input signal) causes a feedback current (I_{fdbk}) to flow through R2. The left-hand side of R2 is at 0 volts (point A) and the right-hand side is at E_{OUT}. Therefore, the feedback current is computed by using the following formula:

$$I_{fdbk} = \frac{-E_{OUT}}{R2}$$

NOTE: The minus sign indicates that E_{OUT} is 180 degrees out of phase with E_{IN} and should not be confused with output polarity.

7-67. Since no current flows into or out of the inverting input of the operational amplifier, any current reaching point A from R1 must flow out of point A through R2. Therefore, the input current (I_{IN}) and the feedback current (I_{fdbk}) must be equal. Now we can develop a mathematical relationship between the input and output signals and R1 and R2 by computing the following:

$$I_{IN} = I_{fdbk}$$

By substitution:

$$\frac{E_{IN}}{R1} = \frac{-E_{OUT}}{R2}$$

If you multiply both sides of the equation by R1:

$$E_{IN} = \frac{-(E_{OUT})(R1)}{R2}$$

If you divide both sides of the equation by E_{OUT}:

$$\frac{E_{IN}}{E_{OUT}} = -\frac{R1}{R2}$$

By inverting both sides of the equation:

$$\frac{E_{OUT}}{E_{IN}} = -\frac{R2}{R1}$$

You should recall that the voltage gain of a stage is defined as the output voltage divided by the input voltage:

$$\frac{E_{OUT}}{E_{IN}}$$

Therefore, the voltage gain of the inverting configuration of the operational amplifier is expressed by the following equation:

$$-\frac{R2}{R1}$$

NOTE: As stated earlier, the minus sign indicates that the output signal is 180 degrees out of phase with the input signal.

Noninverting Configuration

7-68. Figure 7-15 shows a noninverting configuration using an operational amplifier. The input signal (E_{IN}) is applied directly to the noninverting (+) input of the operational amplifier. Feedback is provided by coupling part of the output signal (E_{OUT}) back to the inverting (-) input of the operational amplifier. R1 and R2 act as a voltage divider that allows only a part of the output signal to be applied as feedback (E_{fdbk}).

7-69. Notice that the input signal, output signal, and feedback signal are all in phase (only the positive alternation of the signal is shown). It may appear as if the feedback is regenerative (positive) because the feedback and input signals are in phase. The feedback is, in reality, degenerative (negative) because the input signal is applied to the noninverting input and the feedback signal is applied to the inverting input. Remember that the operational amplifier will react to the difference between the two inputs.

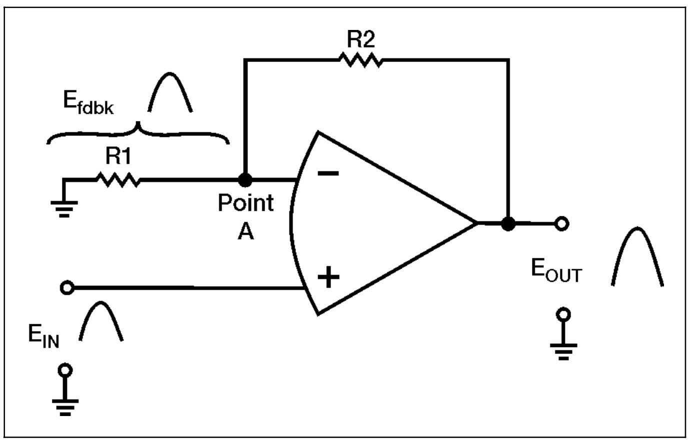


Figure 7-15. Noninverting Configuration

7-70. Just as in the inverting configuration, the feedback signal is equal to the input signal (for all practical purposes). However, this time the feedback signal is in phase with the input signal. This is computed as follows:

$$E_{IN} = E_{fdbk}$$

Given this condition, you can calculate the gain of the stage in terms of the resistors (R1 and R2). The gain of the stage is defined as follows:

$$\text{Gain} = \frac{E_{OUT}}{E_{IN}}$$

Since:

$$E_{IN} = E_{fdbk}$$

Then:

$$\text{Gain} = \frac{E_{OUT}}{E_{fdbk}}$$

7-71. The feedback signal (E_{fdbk}) can be shown in terms of the output signal (E_{OUT}) and the voltage divider (R1and R2). The voltage divider has the output signal on one end and ground (0 volts) on the other end. The feedback signal is that part of the output signal developed by R1 (at point A). Another way to look at it is that the feedback signal is the amount of output signal left (at point A) after part of the output signal has been dropped by R2. In either case, the feedback signal (E_{fdbk}) is the ratio of R1 to the entire voltage divider (R1 + R2) multiplied by the output signal (E_{OUT}).

7-72. Mathematically, the relationship of the output signal, feedback signal, and voltage divider is computed as follows:

$$E_{fdbk} = \frac{R1}{R1 + R2}(E_{OUT})$$

If you divide both sides of the equation by E_{OUT}:

$$\frac{E_{fdbk}}{E_{OUT}} = \frac{R1}{R1 + R2}$$

By inverting both sides of the equation:

$$\frac{E_{OUT}}{E_{fdbk}} = \frac{R1 + R2}{R1}$$

Separating the right-hand side:

$$\frac{E_{OUT}}{E_{fdbk}} = \frac{R1}{R1} + \frac{R2}{R1}$$

Remember:

$$\text{Gain} = \frac{E_{OUT}}{E_{fdbk}}$$

Therefore, by substitution:

$$\text{Gain} = \frac{R2}{R1} + 1$$

7-73. You can now see that the resisters determine the gain of the noninverting configuration. The formula is different from the one used for the inverting configuration; however, the gain is still determined by the values of R1 and R2.

BANDWIDTH LIMITATIONS

7-74. As with most amplifiers, the gain of an operational amplifier varies with frequency. The specification sheets for operational amplifiers will usually state the open-loop (no feedback) gain for DC (or 0 Hz). At higher frequencies, the gain is much lower. In fact, for an operational amplifier, the gain decreases quite rapidly as frequency increases.

7-75. Figure 7-16 shows the open-loop (no feedback) frequency-response curve for a typical operational amplifier. Remember, bandwidth is measured to the half-power points of a frequency-response curve. The frequency-response curve shows that the bandwidth is only 10 Hz with this configuration. The unity gain point, where the signal out will have the same amplitude as the signal in (the point at which the gain of the amplifier is 1), is 1 MHz for the amplifier. As you can see, the frequency response of this amplifier drops off quite rapidly.

7-76. Remember, most operational amplifiers are used in a closed-loop configuration. When you look at the frequency-response curve for a closed-loop configuration, one of the most interesting and important aspects of the operational amplifier is that the use of degenerative feedback increases the bandwidth of an operational amplifier circuit. This is just another example of the difference between the operational amplifier and the operational-amplifier circuit (which includes the components in addition to the operational amplifier). You should also be able to see that the external resistors not only affect the gain of the circuit, but the bandwidth as well.

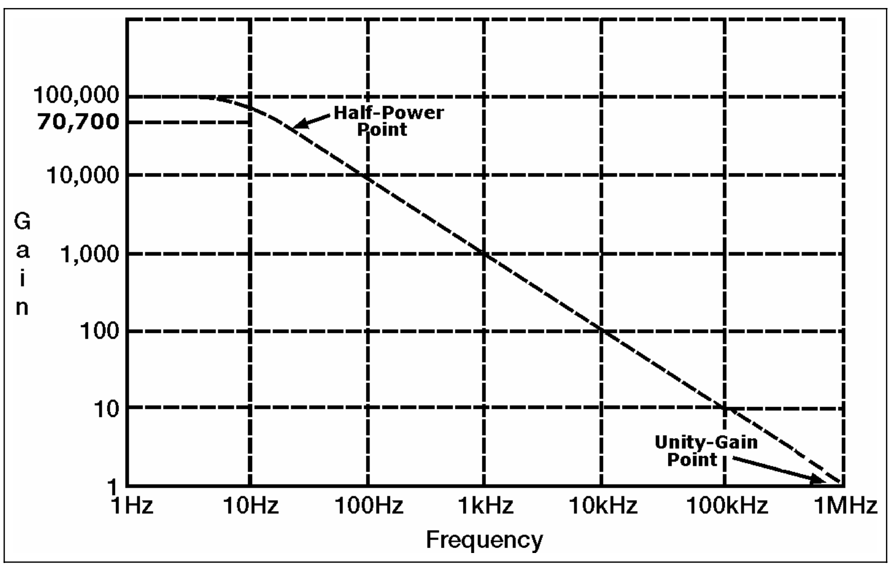


Figure 7-16. Open-loop Frequency-response Curve

7-77. Figure 7-17 should help to show you how the gain and bandwidth of a closed-loop, operational-amplifier circuit are related. Figure 7-17 shows the frequency-response curve that is for a circuit in which degenerative feedback has been used to decrease the circuit gain to 100 (from 100,000 for the operational amplifier). Notice that the half-power point of this curve is just slightly above 10 KHz.

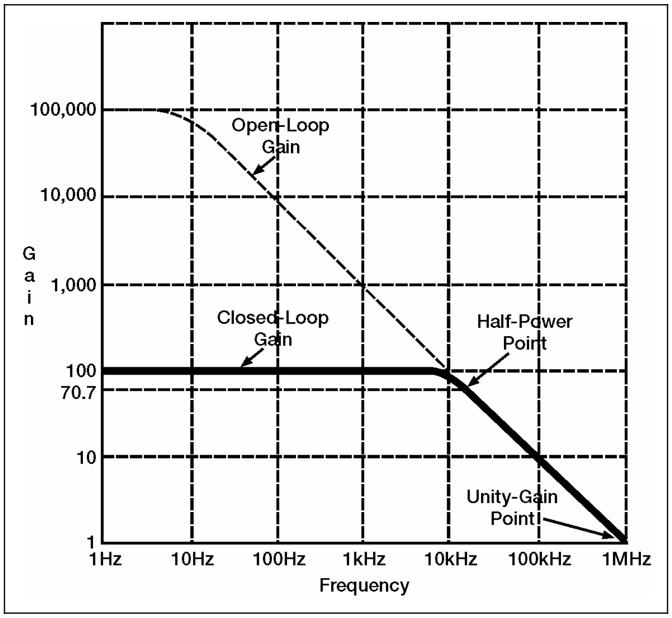


Figure 7-17. Closed-loop Frequency-response Curve for Gain of 100

7-78. In Figure 7-18, more feedback has been used to decrease the gain of the circuit to 10. Now the bandwidth of the circuit is extended to about 100 KHz.

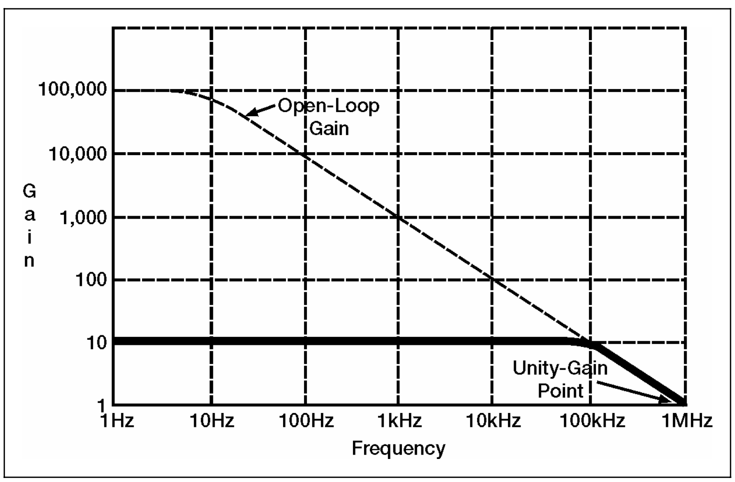


Figure 7-18. Closed-loop Frequency-response Curve for Gain of 10

7-79. The relationship between circuit gain and bandwidth in an operational-amplifier circuit can be expressed by the GAIN-BANDWIDTH PRODUCT (GAIN x BANDWIDTH = UNITY GAIN POINT). In other words, for operational-amplifier circuits, the gain times the bandwidth for one configuration of an operational amplifier will equal the gain times the bandwidth for any other configuration of the same operational amplifier. In other words, when the gain of an operational-amplifier circuit is changed (by changing the value of feedback or input resistors), the bandwidth also changes. But the gain times the bandwidth of the first configuration will equal the gain times the bandwidth of the second configuration. The following example should help you to understand this concept.

7-80. Figures 7-16, 7-17, and 7-18 show the frequency-response curves that have a gain-bandwidth product of 1,000,000. In Figure 7-16 the gain is 100,000 and the bandwidth is 10 Hz. The gain-bandwidth product is 100,000 times 10 Hz, or 1,000,000. In Figure 7-17, the gain has been reduced to 100 and the bandwidth increases to 10 KHz. The gain-bandwidth product is 100 times 10,000 Hz that is also equal to 1,000,000. In Figure 7-18 the gain has been reduced to 10 and the bandwidth is 100 KHz. The gain-bandwidth product is 10 times 100,000 Hz, which is 1,000,000. If the gain were reduced to 1, the bandwidth would be 1 MHz (which is shown on the frequency-response curve as the unity gain point) and the gain-bandwidth product would still be 1,000,000.

APPLICATIONS OF OPERATIONAL AMPLIFIERS

7-81. Operational amplifiers are used in so many different ways that is not possible to describe all of the applications. Entire books have been written on the subject of operational amplifiers. Some books are devoted entirely to the applications of operational amplifiers and are not concerned with the theory of operation or other circuits at all. This TC, as introductory material on operational amplifiers, will show you only two common applications of the operational amplifier (the summing amplifier and the difference amplifier). For ease of explanation, the circuits shown for these applications will be explained with DC inputs and outputs. However, the circuit will work as well with AC signals.

Summing Amplifier (Adder)

7-82. Figure 7-19 is the schematic of a two-input adder that uses an operational amplifier. The output level is determined by adding the input signals together (although the output signal will be of opposite polarity compared to the sum of the input signals).

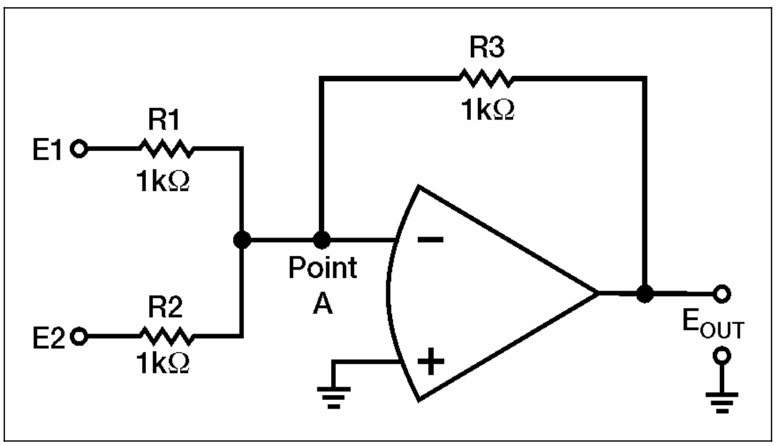


Figure 7-19. Two-input Adder

7-83. If the signal on input number one (E1) is +3 volts and the signal on input number two (E2) is +4 volts, the output signal (E_{OUT}) should be -7 volts [(+3 V) + (+4 V) = +7 V and change the polarity to get -7 V]. With +3 volts at E1 and 0 volts at point A (which is at virtual ground), the current through R1 must be 3 milliamperes. You can compute this as follows:

$$I_{R1} = \frac{E1}{R1}$$

$$I_{R1} = \frac{+3V}{1k\Omega}$$

$$I_{R1} = +3mA$$

NOTE: The + sign indicates a current flow from right to left.

7-84. Using the same type of calculation (with +4 volts at E2 and 0 volts at point A) the current through R2 must be 4 milliamps. This means that a total of 7 milliamps is flowing from point A through R1 and R2. If 7 milliamps is flowing from point A, then 7 milliamps must be flowing into point A. The 7 milliamps flowing into point A flows through R3 causing 7 volts to be developed across R3. With point A at 0 volts and 7 volts developed across R3, the voltage potential at E_{OUT} must be -7 volts. Figure 7-20 shows these voltages and currents.

7-85. An adder circuit is not restricted to two inputs. By adding resistors in parallel to the input terminals, any number of inputs can be used. The adder circuit will always produce an output that is equal to the sum of the input signals but opposite in polarity. Figure 7-21 shows a five input adder circuit with voltages and currents indicated.

7-86. Besides adders, there are other types of summing amplifiers. A summing amplifier can be designed to amplify the results of adding the input signals. This type of circuit actually multiplies the sum of the inputs by the gain of the circuit. You can compute (for a three-input circuit) as follows:

$$E_{OUT} = \text{gain } (E1 + E2 + E3)$$

If the circuit gain is -10:

$$E_{OUT} = -10\ (E1 + E2 + E3)$$

7-87. The gain of the circuit is determined by the ratio between the feedback resistor and the input resistors. To change Figure 7-19 to a summing amplifier with a gain of -10, you would replace the feedback resistor (R3) with a 10-kilohm resistor. Figure 7-22 shows this new circuit. If this circuit is designed correctly and the input voltages (E1 and E2) are +2 volts and +3 volts, respectively, the output voltage (E_{OUT}) should be:

$$E_{OUT} = \text{gain } (E1 + E2)$$

$$E_{OUT} = -10\ ([+2\text{ V}] + [+3\text{ V}])$$

$$E_{OUT} = -10\ (+5\text{ V})$$

$$E_{OUT} = -50\text{ V}$$

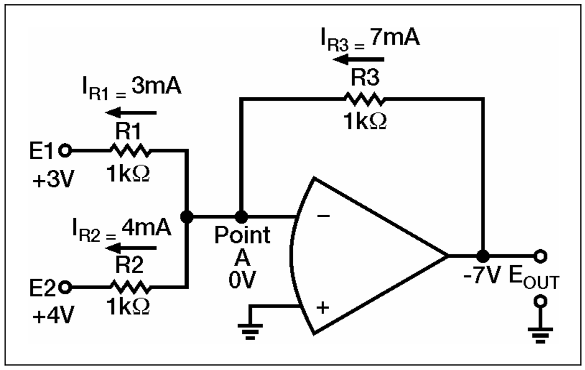
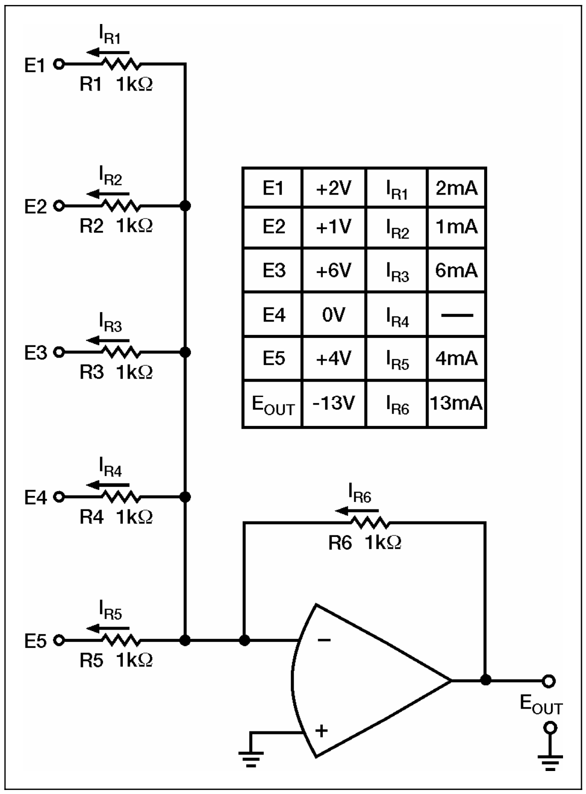


Figure 7-20. Current and Voltage in a Two-input Adder



E1	+2V	I_{R1}	2mA
E2	+1V	I_{R2}	1mA
E3	+6V	I_{R3}	6mA
E4	0V	I_{R4}	—
E5	+4V	I_{R5}	4mA
E_{OUT}	-13V	I_{R6}	13mA

Figure 7-21. Five-input Adder

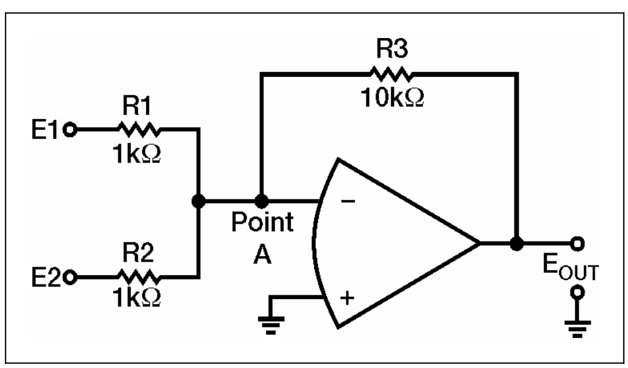


Figure 7-22. Summing Amplifier

7-88. To see if this output (-50 V) is what the circuit will produce with the inputs (+2 V and +3V), start by calculating the currents through the input resistors, R1 and R2 (remember that point A is at virtual ground):

$$I_{R1} = \frac{E1}{R1}$$

$$I_{R1} = \frac{2\,V}{1\,k\Omega}$$

$$I_{R1} = 2\,mA$$

- - - - - - - -

$$I_{R2} = \frac{E2}{R2}$$

$$I_{R2} = \frac{3\,V}{1\,k\Omega}$$

$$I_{R2} = 3\,mA$$

Next, calculate the current through the feedback resistor (R3):

$I_{R3} = -(I_{R1} + I_{R2})$

$I_{R3} = -(2\text{ mA} + 3\text{ mA})$

$I_{R3} = -5\text{ mA}$

NOTE: The minus sign indicates current flow from left to right.

Finally, calculate the voltage dropped across R3 (which must equal the output voltage):

$E_{OUT} = (I_{R3} \times R3)$

$E_{OUT} = (-5\text{ mA} \times 10\text{ k}\Omega)$

$E_{OUT} = -50\text{ V}$

As you can see, this circuit performs the function of adding the inputs together and multiplying the result by the gain of the circuit.

7-89. One final type of summing amplifier is the scaling amplifier. This circuit multiplies each input by a factor (the factor is determined by circuit design) and then adds these values together. The factor that is used to multiply each input is determined by the ratio of the feedback resistor to the input resistor. For example, you could design a circuit that would produce the following output from three inputs (E1, E2, E3):

$$[(2 \times E1) + (4 \times E2) + (3 \times E3)]$$

Using input resistors R1 for input number one (E1), R2 for input number two (E2), R3 for input number three (E3), and R4 for the feedback resistor, you could calculate the values for the resistors as follows:

$$2 = \frac{R4}{R1}$$

$$4 = \frac{R4}{R2}$$

$$3 = \frac{R4}{R3}$$

Any resistors that will provide the ratios shown above could be used. If the feedback resistor (R4) is a 12-kilohm resistor, the values of the other resistors would be calculated as follows:

$$2 = \frac{12\ \text{k}\Omega}{R1}$$

$$2(R1) = 12\,\text{k}\Omega$$

$$R1 = 6\,\text{k}\Omega$$

- - - - - - - - - - - - -

$$4 = \frac{12\,\text{k}\Omega}{R2}$$

$$4(R2) = 12\,\text{k}\Omega$$

$$R2 = 12\,\text{k}\Omega$$

- - - - - - - - - - - - -

$$3 = \frac{12\,\text{k}\Omega}{R3}$$

$$3(R3) = 12\,\text{k}\Omega$$

$$R3 = 4\,\text{k}\Omega$$

7-90. Figure 7-23 is the schematic diagram of a scaling amplifier with the values from the previous calculations. To see if the circuit will produce the desired output, calculate the currents and voltages as done for the previous circuits.

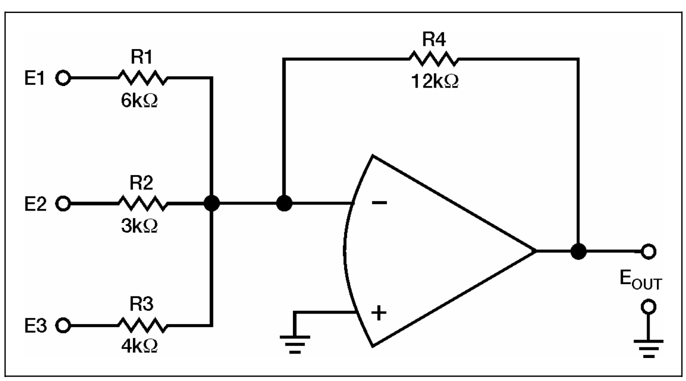


Figure 7-23. Scaling Amplifier

With:

E1 = +12 V

E2 = +3 V

E3 = +8 V

the output should be:

E_{OUT} = – [(2 x E1) + (4 X E2) + (3 x E3)]

E_{OUT} = – [(2 x + 12 V) + (4 x + 3 V) + (3 x + 8 V)]

E_{OUT} = [(+24 V) + (+12 V) + (+24 V)]

E_{OUT} = -60 V

Calculate the current for each input:

$$I_{R1} = \frac{E1}{R1}$$
$$I_{R1} = \frac{+12\,V}{6\,k\Omega}$$
$$I_{R1} = +2\,mA$$
– – – – – – – –
$$I_{R2} = \frac{E2}{R2}$$
$$I_{R2} = \frac{+3\ V}{3\,k\Omega}$$
$$I_{R2} = +1\,mA$$
– – – – – – – –
$$I_{R3} = \frac{E3}{R3}$$
$$I_{R3} = \frac{+8\,V}{4\,k\Omega}$$
$$I_{R3} = +2\,mA$$
– – – – – – – –
$$I_{R4} = -(I_{R1} + I_{R2} + I_{R3})$$
$$I_{R4} = -(2\,mA + 1\,mA + 2\,mA)$$
$$I_{R4} = -5\,mA$$

Calculate the output voltage:

E_{OUT} = B_{R4}

E_{OUT} = (I_{R4} x R_4)

E_{OUT} = (-5 mA) x 12 kΩ

E_{OUT} = -60 V

You have now seen how an operational amplifier can be used in a circuit as an adder, a summing amplifier, and a scaling amplifier.

Difference Amplifier (Subtractor)

7-91. A difference amplifier will produce an output based on the difference between the input signals. The subtractor circuit (see Figure 7-24) will produce the following output:

E_{OUT} = E2 - E1

7-92. Normally, difference amplifier circuits have the ratio of the inverting input resistor to the feedback resistor equal to the ratio of the noninverting input resistors. In other words, for Figure 7-24:

$$\frac{R1}{R3} = \frac{R2}{R4}$$

and by inverting both sides:

$$\frac{R3}{R1} = \frac{R4}{R2}$$

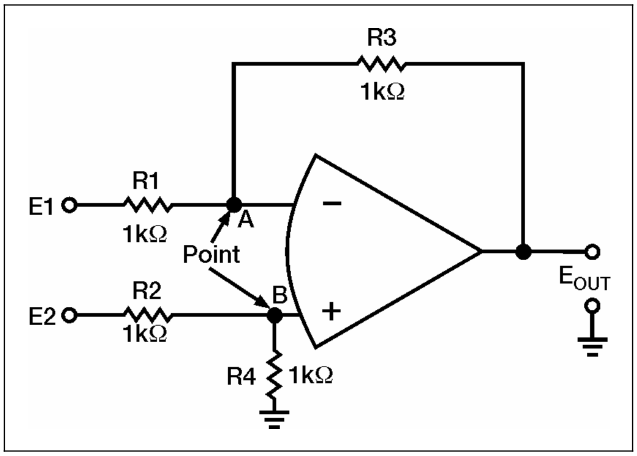


Figure 7-24. Subtractor Circuit

7-93. For an easy explanation for the circuit shown in Figure 7-24, all the resistors have a value of 1 kilohm. However, any value could be used as long as the above ratio is true. For a subtractor circuit, the values of R1 and R3 must also be equal, and therefore, the values of R2 and R4 must be equal. It is not necessary that the value of R1 equal the value of R2. Using Figure 7-24, assume that the input signals are:

E1 = +3 V

E2 = +12 V

The output signal should be:

E_{OUT} = E2 - E1

E_{OUT} = (+12 V) - (+3 V)

E_{OUT} = +9 V

To check this output, first compute the value of R2 plus R4:

R2 + R4 = 1 kΩ + 1 kΩ

R2+ R4 = 2 kΩ

With this value, compute the current through R2 (I_{R2}) (indicating current flow from left to right):

$$I_{R2} = \frac{E2}{R2 + R4}$$

$$I_{R2} = \frac{+12\,V}{2\,k\Omega}$$

$$I_{R2} = +6\,mA$$

Next, compute the voltage drop across R2 (E_{R2}):

E_{R2} = R2 x I_{R2}

E_{R2} = 1 kΩ x (+6 mA)

E_{R2} = +6 V

Then compute the voltage at point B:

Voltage at point B = E2 - E_{R2}

Voltage at point B = (+12 V) - (+6 V)

Voltage at point B = +6 V

Since point B and point A will be at the same potential in an operational amplifier:

Voltage at point A = +6 V

Now compute the voltage developed by R1 (E_{R1}):

E_{R1} = (voltage at point A) - (E1)

E_{R1} = (+6 V) - (+3 V)

E_{R1}= +3 V

Compute the current through R1 (I_{R1}):

$$I_{R1} = \frac{E_{R1}}{R1}$$

$$I_{R1} = \frac{+3\,V}{1\,k\Omega}$$

$$I_{R1} = +3\,mA$$

$$\text{Since:} \qquad I_{R1} = I_{R3}$$

$$\text{Then:} \qquad I_{R3} = +3\,mA$$

Compute the voltage developed by R3 (E_{R3}):

E_{R3} = (R3) x (I_{R3})

E_{R3} = (I kΩ) x (+3 mA)

E_{R3} = +3 V

Add this to the voltage at point A to compute the output voltage (E_{OUT}):

E_{OUT} = (E_{R3}) + (voltage at point A)

E_{OUT} = (+3 V) + (+6 V)

E_{OUT} = +9 V

7-94. The circuit shown in Figure 7-24 functions as a subtractor. Just as an adder is only one kind of summing amplifier, a subtractor is only one kind of difference amplifier. A difference amplifier can amplify the difference between two signals. For example, with two inputs (E1 and E2) and a gain of five, a difference amplifier will produce an output signal that is:

E_{OUT} = 5 (E2 - E1)

7-95. The difference amplifier that will produce that output is shown in Figure 7-25. Notice that this circuit is the same as the subtractor shown in Figure 7-24 except for the values of R3 and R4. The gain of this difference amplifier is:

$$\text{Gain} = \frac{R3}{R1}$$

$$\text{Gain} = \frac{5k\Omega}{1k\Omega}$$

$$\text{Gain} = 5$$

and since:

$$\frac{R3}{R1} = \frac{R4}{R2}$$

then, for a difference amplifier:

$$\text{Gain} = \frac{R3}{R1} = \frac{R4}{R2}$$

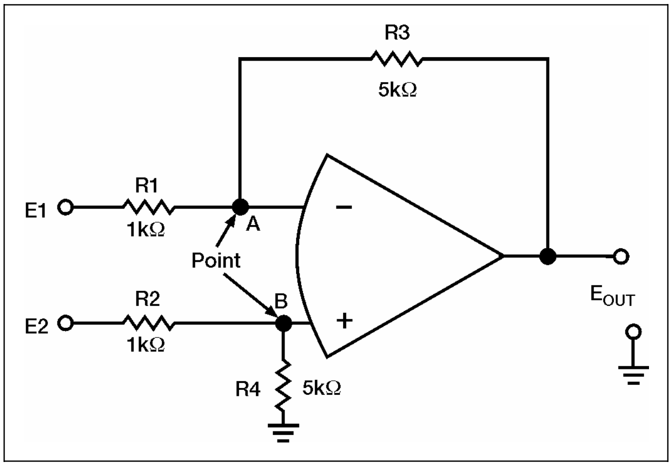


Figure 7-25. Difference Amplifier

7-96. With the same inputs that were used for the subtractor (E1 = +3 V; E2 = +12 V) the output of the difference amplifier should be five times the output of the subtractor (E_{OUT} = +45 V). Following the same steps used for the subtractor, first compute the value of R2 plus R4:

R2 + R4 = 1 kΩ + 5 kΩ

R2 + R4 = 6 kΩ

With this value, compute the current through R2 (I_{R2}):

$$I_{R2} = \frac{E2}{R2 = R4}$$

$$I_{R2} = \frac{+12V}{6\,k\Omega}$$

$$I_{R2} = +2\,mA$$

Next, compute the voltage drop across R2 (E_{R2}):

E_{R2} = (R2) x (I_{R2})

E_{R2} = (1 k Ω) x (+2 mA)

E_{R2} = +2 V

Then, compute the voltage at point B:

Voltage at point B = E2 - E_{R2}

Voltage at point B = (+12 V) - (+2 V)

Voltage at point B = +10 V

Since point A and point B will be the same potential in an operational amplifier:

Voltage at point A = +10 V

Now compute the voltage developed by the R1 (E_{R1}):

E_{R1} = (voltage at point A) - (El)

E_{R1} = (+10 V) - (+3 V)

E_{R1} = +7 V

Compute the current through R1 (I_{R1}):

$$I_{R1} = \frac{E_{R1}}{R1}$$

$$I_{R1} = \frac{+7\,V}{k\,\Omega}$$

$$I_{R1} = +7\,mA$$

Since: $I_{R1} = I_{R3}$

Then: $I_{R3} = +7\,mA$

Compute the voltage developed by R3 (E_{R3}):

E_{R3} = R3 x I_{R3}

E_{R3} = (5 kΩ) x (+7 mA)

E_{R3} = +35 V

Add this voltage to the voltage at point A to compute the output voltage (E_{OUT}):

E_{OUT} = (E_{R3}) + (voltage at point A)

E_{OUT} = (+35 V) + (+10 V)

B_{OUT} = +45 V

This was the output desired, so the circuit works as a difference amplifier.

MAGNETIC AMPLIFIERS

7-97. You have seen various ways that electron tubes and transistors can be used to amplify signals. There is another type of amplifier in use, the MAGNETIC AMPLIFIER (sometimes called the MAG AMP).

7-98. The magnetic amplifier has certain advantages over other types of amplifiers. These advantages include:

- High efficiency (up to 90 percent).
- Reliability (long life, freedom from maintenance, and reduction of spare parts inventory).

- Ruggedness (shock and vibration resistance, high overload capability, and freedom from effects of moisture).
- No warm-up time.

The magnetic amplifier has no moving parts and can be hermetically sealed within a case similar to the conventional dry-type transformer.

7-99. The magnetic amplifier also has a few disadvantages. These disadvantages include:

- Cannot handle low-level signals.
- Not useful at high frequencies
- Has a time delay associated with the magnetic effects.
- The output waveform is not an exact reproduction of the input waveform (poor fidelity).

7-100. As mentioned, the magnetic amplifier does not amplify magnetism, but uses electromagnetism to amplify a signal. It is a power amplifier with a very limited frequency response. Technically, it falls into the classification of an audio amplifier. However, since the frequency response is normally limited to 100 Hz and below, the magnetic amplifier is more correctly called a low-frequency amplifier.

7-101. The basic principle of a magnetic amplifier is very simple (remember, all amplifiers are current-control devices). A magnetic amplifier uses a changing inductance to control the power delivered to a load.

BASIC OPERATION OF A MAGNETIC AMPLIFIER

7-102. Figure 7-26 shows a simple circuit with a variable inductor in series with a resistor (representing a load). The voltage source is 100 volts at 60 Hz.

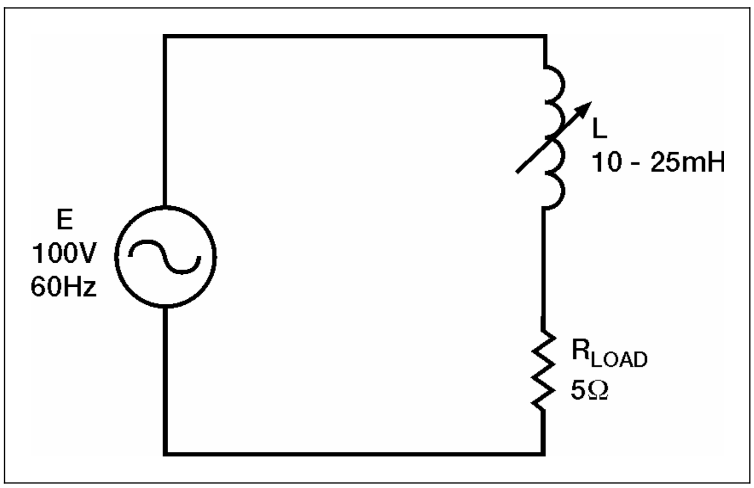


Figure 7-26. Variable Inductor in Series With a Load

7-103. When the inductance decreases, the end result is that the power in the load (true power) increases. The following formulas show how each is affected by a decrease in inductance.

$X_L = 2\pi fL$ (inductive reactance in the circuit)

$Z = \sqrt{X_L^2 + R^2}$ (impedance in the circuit)

$I = \frac{E}{Z}$ (current in the circuit)

True power = I^2R (true power or power in the load)

As inductance (L) decreases, X_L decreases. As X_L decreases, Z decreases. As Z decreases, I increases. Finally, as I increases, true power increases. This general conclusion can be confirmed by using some actual values of inductance in the formulas along with other values from Figure 7-26.

7-104. If the value of inductance is 23 millihenries, the formulas yield the following values:

$$X_L = 2\pi fL$$
$$X_L = (2)(3.14)(60\,Hz)(23\,mH)$$
$$X_L = 8.67\,\Omega \text{ (rounded off)}$$
$$Z = \sqrt{X_L^2 + R^2}$$
$$Z = \sqrt{(8.67\,\Omega^2 + (5\,\Omega)^2}$$
$$Z = \sqrt{100.1689\,\Omega}$$
$$Z = 10\,\Omega \text{ (rounded off)}$$
$$I = \frac{E}{Z}$$
$$I = \frac{100\,V}{10\,\Omega}$$
$$I = 10\,A$$
$$\text{TruePower} = I^2R$$
$$\text{True Power} = (10A)^2 \text{ x } (5\Omega5$$
$$\text{True Power} = 500 \text{ watts}$$

If the value of inductance is decreased to 11.7 millihenries, the formulas yield the following values:

$$X_L = 2\pi fL$$
$$X_L = (2)(3.14)(60\,Hz)(11.7\,mH)$$
$$X_L = 4.41\Omega\ (rounded off)$$
$$Z = \sqrt{X_L{}^2 + R^2}$$
$$Z = \sqrt{(4.41\Omega^2 + (5\Omega)^2}$$
$$Z = \sqrt{44.4481\Omega}$$
$$Z = 6.67\Omega\ (rounded off)$$
$$I = \frac{E}{Z}$$
$$I = \frac{100\,V}{6.67\Omega}$$
$$I = 15\,A\ (rounded off)$$
$$True\ Power = I^2R$$
$$True\ Power = (15\,A)^2\ x\ (5\Omega)$$
$$True\ Power = 1125\,W$$

So, a decrease in inductance of 11.3 millihenries (23 mH - 11.7 mH) causes an increase in power to the load (true power) of 625 watts (1125 W - 500 W). If it took 1 watt of power to change the inductance by 11.3 millihenries (by some electrical or mechanical means), Figure 7-26 would represent a power amplifier with a gain of 625.

METHODS OF CHANGING INDUCTANCE

7-105. Changing the inductance of a coil enables the control of power to a load. There are methods that are available to change the inductance.

7-106. Permeability was defined as the measure of the ability of a material to act as a path for additional magnetic lines of force. Soft iron was presented as having high permeability compared with air. In fact, the permeability of unmagnetized iron is 5,000 while air has a permeability of 1. A nonmagnetized piece of iron has high permeability because the tiny molecular magnets (Weber's Theory) or the directions of electron spin (Domain Theory) can be aligned by a magnetic field. As they align, they act as a path for the magnetic lines of force.

7-107. The inductance of a coil increases directly as the permeability of the core material increases. If a coil is wound around an iron core, the permeability of the core is 5,000. If the iron is pulled part way out of the coil of wire, the core is part iron and part air. Therefore, the permeability of the core decreases. As the permeability of the core decreases, the inductance of the coil decreases. This increases the power delivered to the load (true power). This relationship is shown in Figure 7-27.

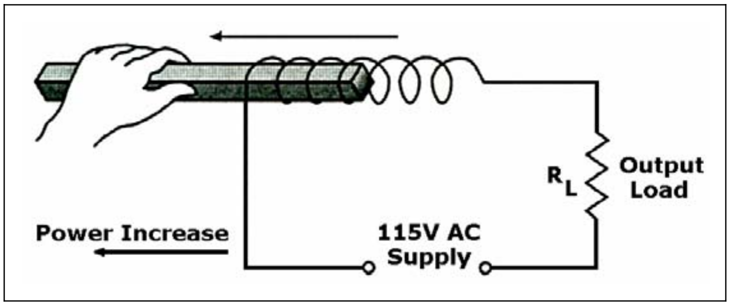


Figure 7-27. Varying Coil Inductance With a Moveable Coil

7-108. The system, shown in Figure 7-27, is not too practical. Even if a motor were used in place of the hand that is shown, the resulting amplifier would be large, expensive, and not easily controlled. If the permeability of a core could be changed by electrical means rather than mechanical, a more practical system would result.

7-109. High permeability depends on there being many molecular magnets (or electron spin directions) that can be aligned to provide a path for magnetic lines of force. If almost all of these available paths are already being used, the material is magnetized and there are no more paths for additional lines of force. The “flux density” (number of lines of force passing through a given area) is as high as it can be. This means that the permeability of the material has decreased. When this condition is reached, the core is said to be saturated, because it is saturated (filled) with all the magnetic lines of force it can pass. At this point, the core has almost the same value of permeability as air (1) instead of the much higher value of permeability (5,000) that it had when it was unmagnetized.

7-110. Of course, the permeability does not suddenly change from 5,000 to 1. The permeability changes as the magnetizing force changes until saturation is reached. At saturation, permeability remains very low no matter how much the magnetizing force increases. If you were to draw a graph of the flux density compared to the magnetizing force, you would have something similar to the graph shown in Figure 7-28. Figure 7-28 also includes a curve representing the value of permeability as the magnetizing force increases. Point “S” in Figure 7-28 is the point of saturation. The flux density does not increase above point “S,” and the permeability is at a steady, low value.

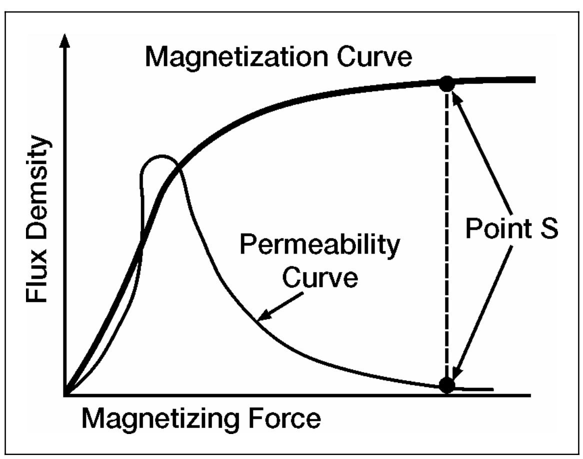


Figure 7-28. Magnetization and Permeability Curves

7-111. You have now seen how a change in the magnetizing force causes a change in permeability. Now we will see how you change the magnetizing force. Magnetizing force is a function of ampere-turns. An ampere-turn is the magnetomotive force developed by 1 ampere of current flowing in a coil of one turn. If you increase the ampere-turns of a coil, the magnetizing force increases. Since it is not practical to increase the number of turns, the easiest way to accomplish this is to increase the current through the coil.

7-112. If you increase the current through a coil, you increase the ampere-turns. By increasing the ampere-turns you increase the magnetizing force. At some point, this causes a decrease in the permeability of the core. With the permeability of the core decreased, the inductance of the coil decreases. As already stated, a decrease in the inductance causes an increase in power through the load. A device that uses this arrangement is called a SATURABLE-CORE REACTOR or SATURABLE REACTOR.

SATURABLE-CORE REACTOR

7-113. A saturable-core reactor is a magnetic-core reactor (coil) whose reactance is controlled by changing the permeability of the core. To change the permeability of the core, vary a unidirectional flux (flux in one direction) through the core.

7-114. Figure 7-29 shows a saturable-core reactor that is used to control the intensity of a lamp. Notice that two coils are wound around a single core. The coil on the left is connected to a rheostat and a battery. This coil is called the control coil because it is part of the control circuit. The coil on the right is connected to a lamp (the load) and an AC source. This coil is called the load coil because it is part of the load circuit.

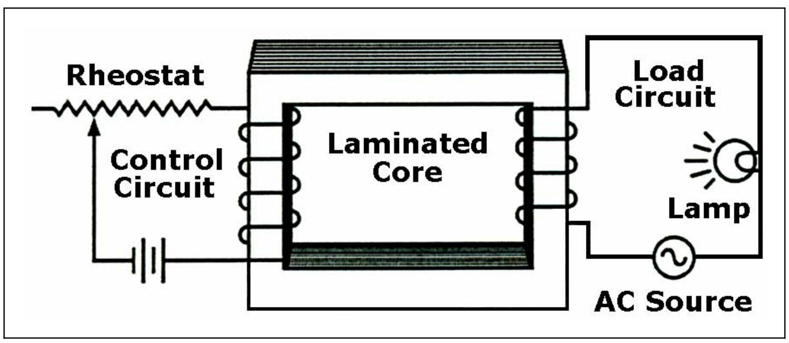


Figure 7-29. Simple Saturable-core Reactor Circuit

7-115. As the wiper (the movable connection) of the rheostat is moved toward the right, there is less resistance in the control circuit. With less resistance, the control-circuit current increases. This causes the amount of magnetism in the core to increase and the inductance of the coil in the load circuit to decrease (because the core is common to both coils). With less inductance in the load circuit, load current increases and the lamp gets brighter.

7-116. Figure 7-30 shows the schematic diagram of this circuit. L1 is the schematic symbol for a saturable-core reactor. The control winding is shown with five loops and the load winding is shown with three loops. The double bar between the inductors stands for an iron core and the symbol that cuts across the two windings is a saturable-core symbol indicating that the two windings share a saturable-core.

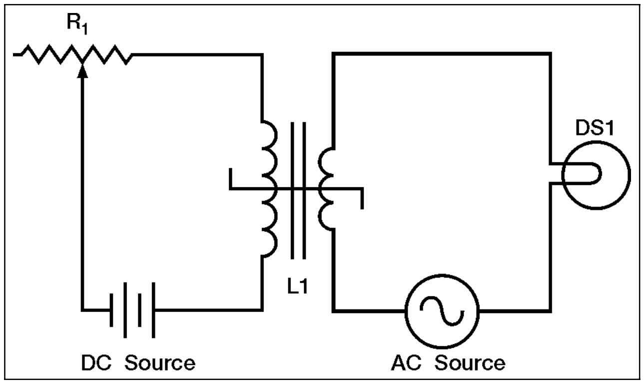


Figure 7-30. Schematic Diagram of a Simple Saturable-core Reactor

7-117. You now have seen the basic operation of a saturable-core reactor. There is one more area to discuss before moving on to the circuitry of a magnetic amplifier. There is a point upon the magnetization curve where the saturable-core reactor should be operated. The ideal operating point is the place in which a small increase in control current will cause a large increase in output power and a small decrease in control current will cause a large decrease in output power. This point is on the flattest portion of the permeability curve (after its peak). Figure 7-31 shows the magnetization and permeability curves for a saturable-core reactor with the ideal operating point (point “0”) indicated. Notice point “0” on the magnetization curve. The portion of the magnetization curve where point “0” is located is called the KNEE OF THE CURVE. The knee of the curve is the point of maximum curvature. It is called the “knee” because it looks like the knee of a leg that is bent. Saturable-core reactors and magnetic amplifiers should be operated on the knee of the magnetization curve.

7-118. When the saturable-core reactor is set at the knee of the magnetization curve, any small increase in control current will cause a large increase in load current. Any small decrease in control current will cause a large decrease in load current. That is why point “0” is the ideal operating point, because small changes in control current will cause large changes in load current. In other words, the saturable-core reactor can amplify the control current. However, a saturable-core reactor is not a magnetic amplifier. Later you will learn how a magnetic amplifier differs from a saturable-core reactor. First you should know a few more things about the saturable-core reactor.

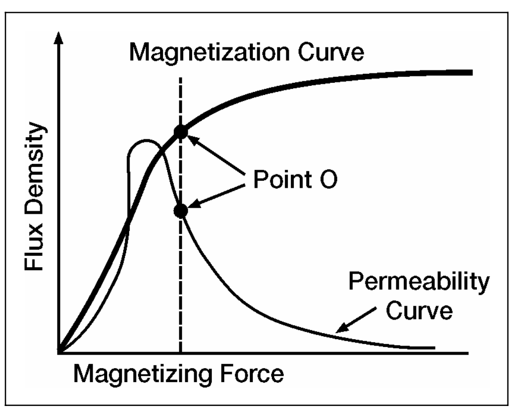


Figure 7-31. Magnetization and Permeability Curves With Operating Point

7-119. If a DC voltage is applied to the control winding of a saturable-core reactor and an AC voltage is applied to the load windings, the AC flux will aid the DC flux on one half cycle and oppose the DC flux on the other half cycle (see Figure 7-32). The dashed-line arrows show the load flux and the solid-line arrows show the control flux. View (A) shows the load and control flux aiding during one half cycle of the AC. View (B) shows the load and control flux opposing during the other half cycle of the AC. This situation causes the operating point of the saturable-core reactor to shift with the applied AC. However, the situation would be better if the load flux was not an influence on the control flux. Figure 7-33 shows a circuit in which this is accomplished.

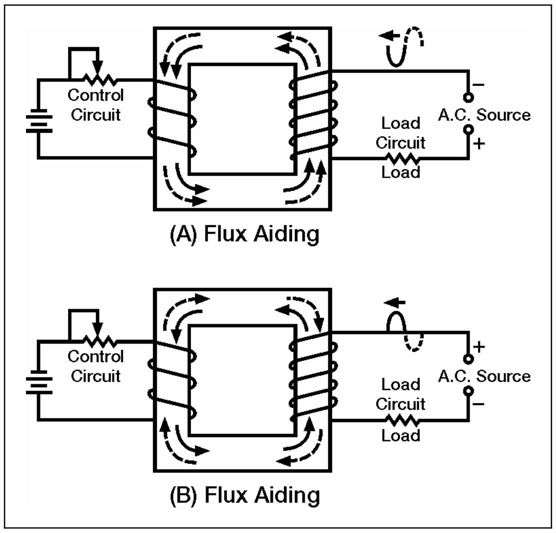


Figure 7-32. Flux Paths in a Saturable-core Reactor

7-120. During the first half cycle, the load circuit flux (dashed-line arrows) cancels in the center leg of the core (see Figure 7-33, view (A)). As a result, there is no effect upon the flux from the control circuit. During the second half cycle, the polarity of the AC (and therefore the polarity of the flux) reverses as shown in view (B). The result is the same as it was during the first half cycle. There is no effect upon the control circuit flux.

7-121. Figure 7-34 shows another approach to solving the problem of load flux affecting control flux. Figure 7-34 shows a toroidal saturable-core reactor. The shape of these cores is a toroid (donut shape). The windings are wound around the cores so that the load flux aids the control flux in one core and opposes the control flux in the other core.

7-122. During the first half cycle, the flux aids in the left core and opposes in the right core (see Figure 7-34, view (A)). During the second half cycle, the flux opposes in the left core and aids in the right core (see Figure 7-34, (view (B)). Regardless of the amount of load flux or polarity of the load voltage, there is no net effect of load flux on control flux.

7-123. Figures 7-33 and 7-34 represent practical, workable saturable-core reactors. Circuits similar to these are actually used to control lighting in auditoriums or electric industrial furnaces. These circuits are sometimes referred to as magnetic amplifiers; however, that is not technically correct. A magnetic amplifier differs from a saturable-core reactor in one important aspect and that is a magnetic amplifier has a rectifier in addition to a saturable-core reactor.

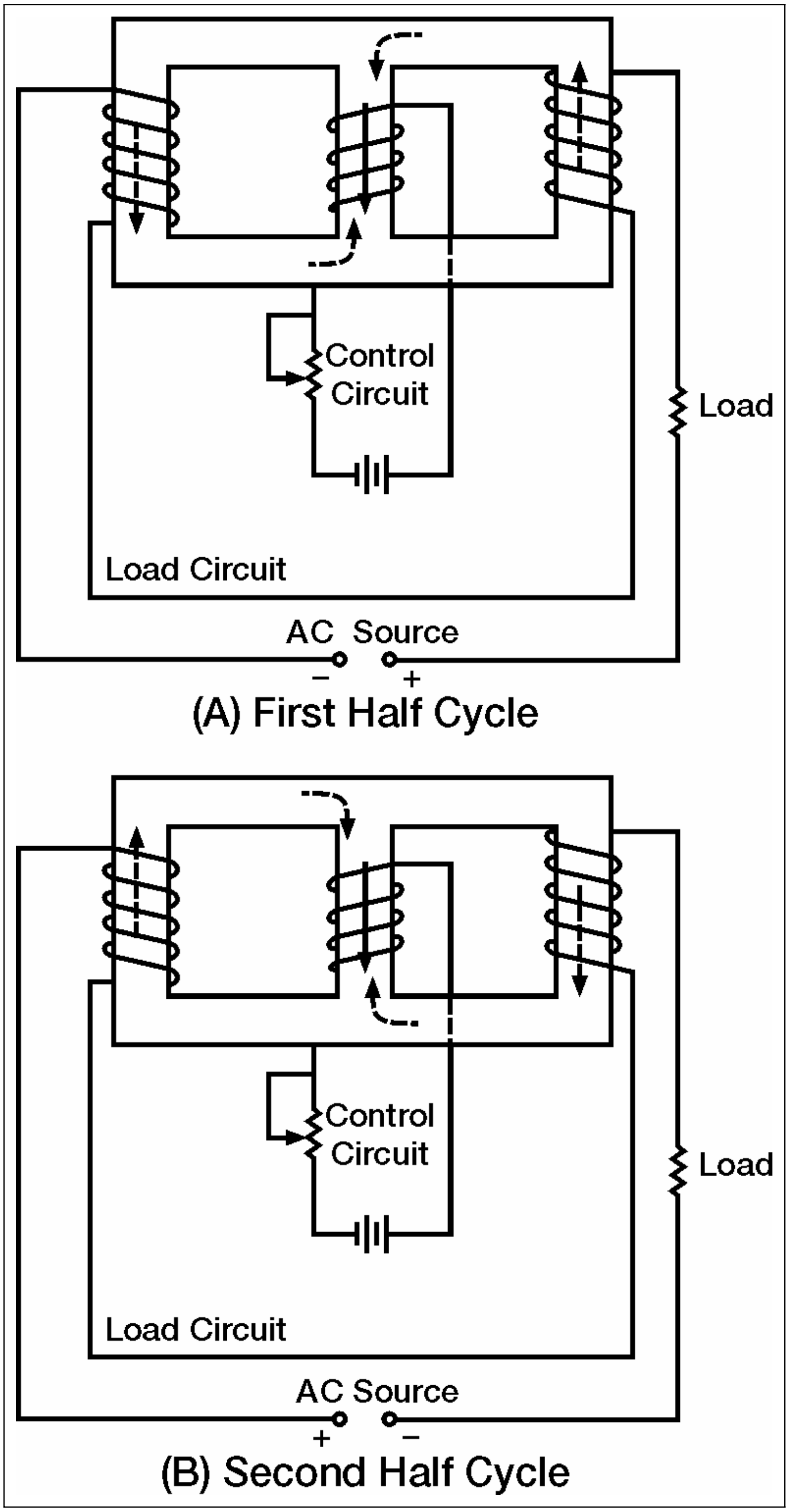


Figure 7-33. Three-legged, Saturable-core Reactor

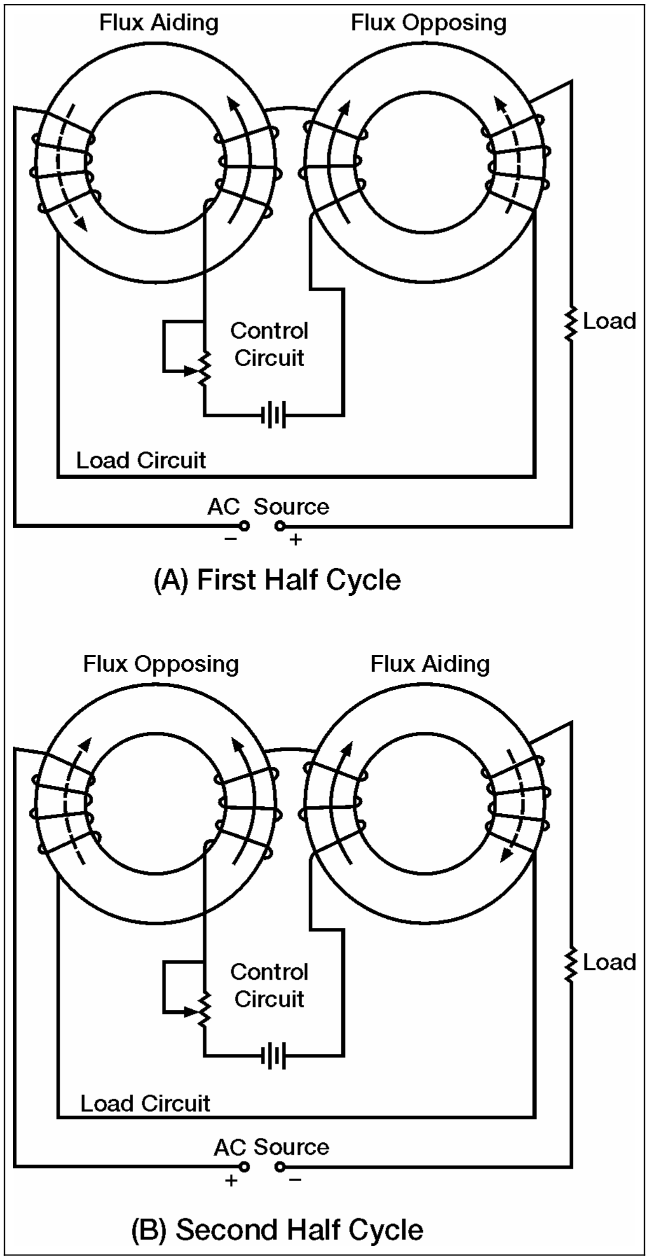


Figure 7-34. Toroidal Saturable-core Reactor

SIMPLIFIED MAGNETIC AMPLIFIER CIRCUITRY

7-124. Even though the saturable-core reactor works, we need to add a rectifier to produce a magnetic amplifier because of hysteresis loss. Hysteresis loss occurs because the AC applied to a coil causes the tiny molecular magnets (or electron-spin directions) to realign as the polarity of the AC changes. This realignment uses up power. The power that is used for realignment is a loss as far as the rest of the circuit is concerned. The power gain is relatively low because of this hysteresis loss in the saturable-core reactor. A rectifier added to the load circuit will eliminate the hysteresis loss and increase the gain. This is because the rectifier allows current to flow in only one direction through the load coils.

7-125. Figure 7-35 shows a simple half-wave magnetic amplifier. This is a half-wave magnetic amplifier because it uses a half-wave rectifier. During the first half cycle of the load voltage, the diode conducts and the load windings develop load flux (shown in view (A) by the dashed-line arrows) The load flux from the two load coils cancels and has no effect on the control flux. During the second half cycle, the diode does not conduct and the load coils develop no flux (shown in view (B)). The load flux never has to reverse direction as it did in the saturable-core reactor, so the hysteresis loss is eliminated.

7-126. Figure 7-35 shows the circuit that is able to use only half of the load voltage (and therefore half the possible load power) since the diode blocks current during half the load-voltage cycle. A full-wave rectifier used in place of CR1 would allow current flow during the entire cycle of load voltage while still preventing hysteresis loss.

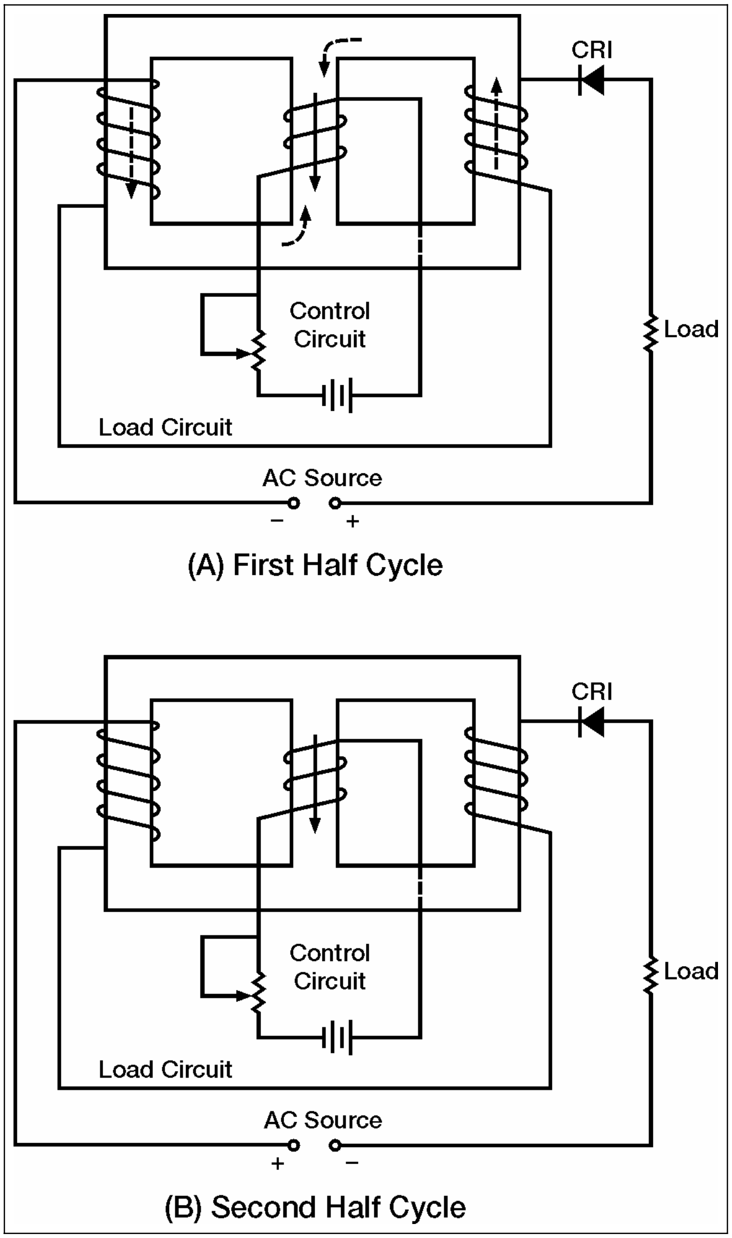


Figure 7-35. Simple Half-wave Magnetic Amplifier

7-127. Figure 7-36 shows a simple full-wave magnetic amplifier. The bridge circuit of CR1, CR2, CR3, and CR4 allows current to flow in the load circuit during the entire load voltage cycle. However, the load current is always in the same direction. This current flow in one direction prevents hysteresis loss. View (A) shows that during the first half cycle of load voltage, current flows through CR1, the load coils, and CR3. View (B) shows that during the second half cycle, load current flows through CR2, the load coils, and CR4.

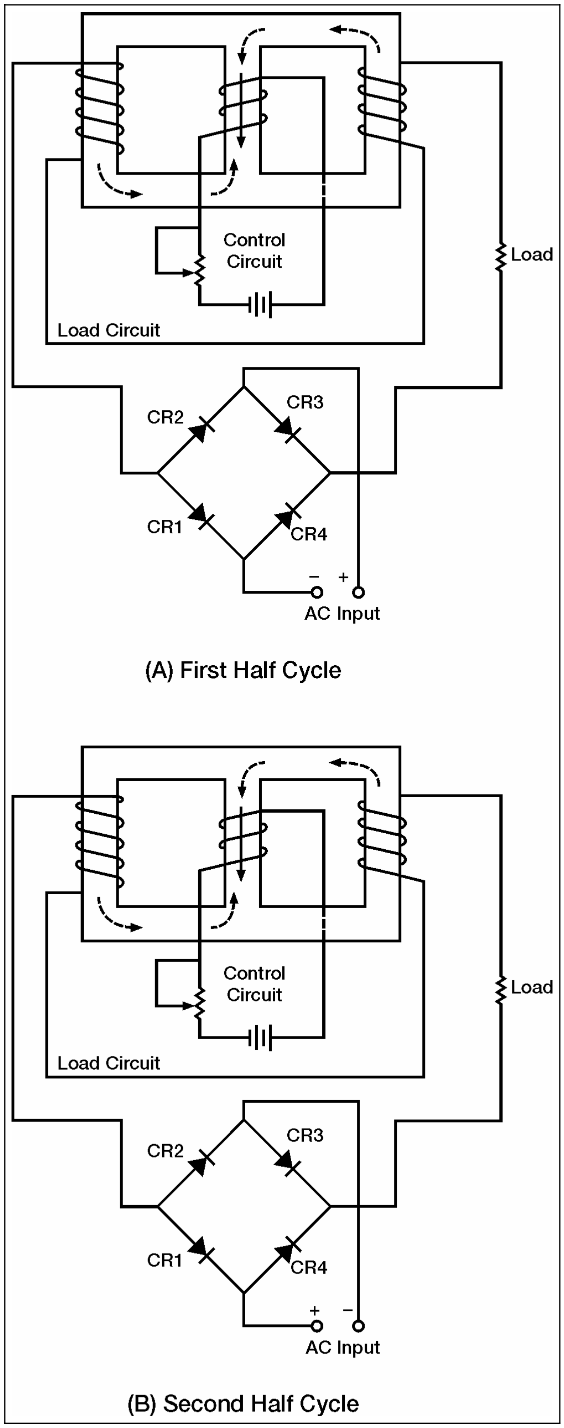


Figure 7-36. Simple Full-wave Magnetic Amplifier

7-128. So far the control circuit of the magnetic amplifier has only been shown with DC applied to it. Magnetic-amplifier control circuits should accept AC input signals as well as DC input signals. As shown earlier in Figure 7-31, a saturable-core reactor has an ideal operating point. Some DC must always be applied to bring the saturable core to that operating point. This DC is called BIAS. The most effective way to apply bias to the saturable core and also allow AC input signals to control the magnetic amplifier is to use a bias winding. Figure 7-37 shows a full-wave magnetic amplifier with a bias winding.

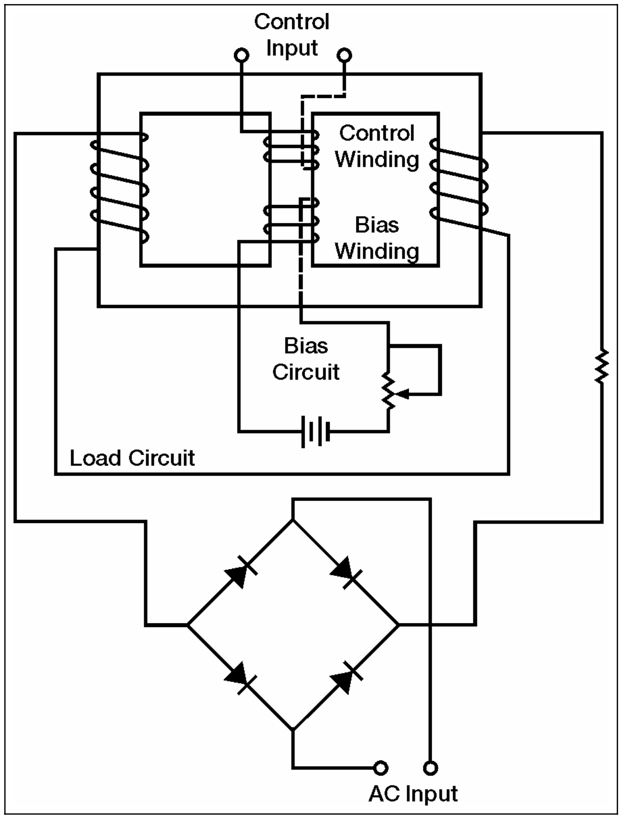


Figure 7-37. Full-wave Magnetic Amplifier With Bias Winding

7-129. Figure 7-37 shows the circuit where the bias circuit is adjusted to set the saturable-core reactor at the ideal operating point. Input signals, represented by the AC source symbol, are applied to the control input. The true power of the load circuit is controlled by the control input signal (AC).

7-130. Figure 7-38 shows the block diagram symbol for a magnetic amplifier. The triangle is the general symbol for an amplifier. The saturable-core reactor symbol in the center of the triangle identifies the amplifier as a magnetic amplifier. Notice the input and output signals shown. The input signal is a small-amplitude, low-power AC signal. The output signal is a pulsating DC with an amplitude that varies. This variation is controlled by the input signal and represents a power gain of 1,000.

7-131. Some magnetic amplifiers are designed so AC goes through the load rather than pulsating DC. You can do this by placing the load in a different circuit position with respect to the rectifier. The principle of the magnetic amplifier remains the same; that is, control current still controls load current.

7-132. Magnetic amplifiers provide a way of accurately controlling large amounts of power. They are used in servo systems, temperature or pressure indicators, and power supplies.

7-133. This chapter has presented only the basic operating theory of saturable-core reactors and magnetic amplifiers. For your convenience, simple schematic diagrams have been used to illustrate this material. When magnetic amplifiers and saturable-core reactors are used in actual equipment, the schematics may be more complex than those you have seen here. You may also find coils used in addition to those presented in this chapter. The TM for the equipment in question should contain the information you need to supplement what you have read in this chapter.

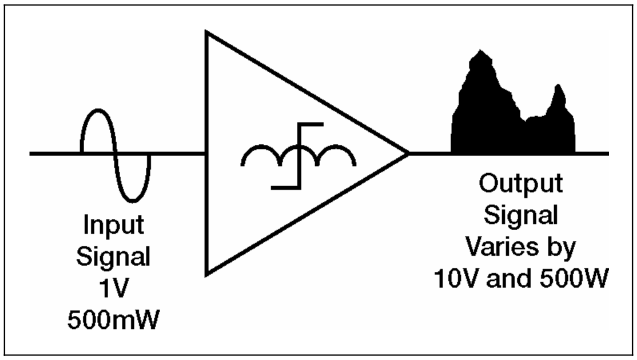
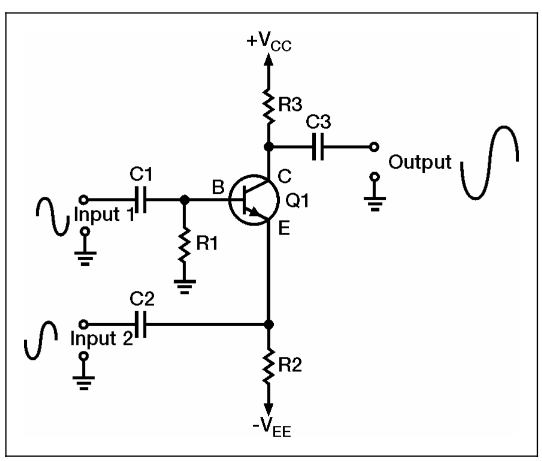


Figure 7-38. Magnetic Amplifier Input and Output Signals

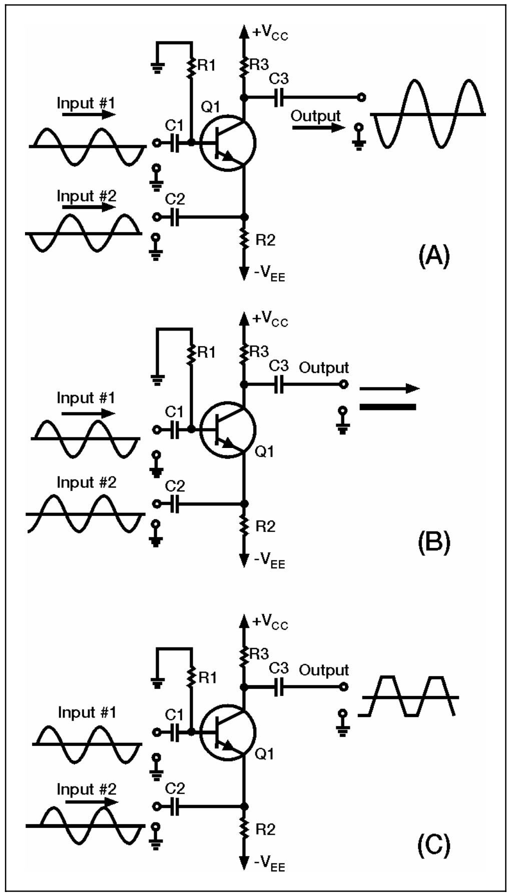
SUMMARY

7-134. Now that we have completed this chapter, the following is a short review of the more important points. Answer the check-on-learning questions, found after the summary, to determine how much you have learned from this chapter.

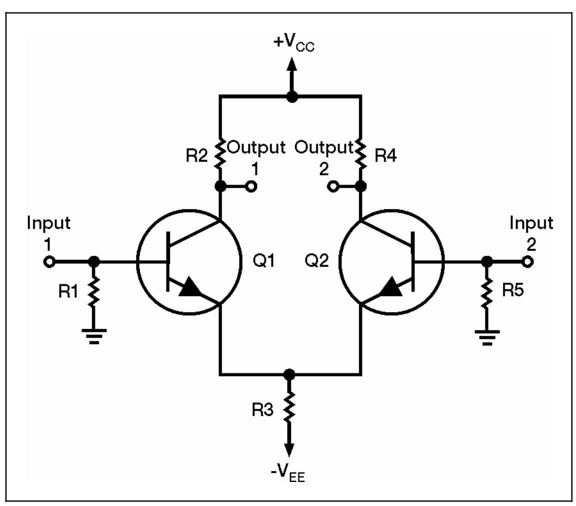
DIFFERENCE AMPLIFIER - any amplifier with an output signal dependent upon the difference between the input signals. Combine the CE and CB configurations in a single transistor to make a two-input, single-output difference amplifier.



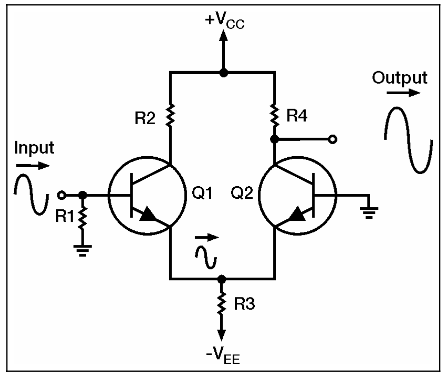
A difference amplifier can have input signals that are ***IN PHASE*** with each other (view A), ***180 DEGREES OUT OF PHASE*** with each other (view B) or ***OUT OF PHASE BY SOMETHING OTHER THAN 180 DEGREES*** with each other (view C).



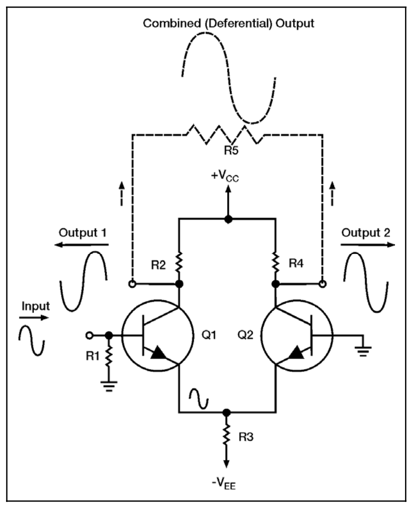
DIFFERENTIAL AMPLIFIER - has two input possible inputs and two possible outputs. The combined output signal is dependent upon the difference between the input signals.



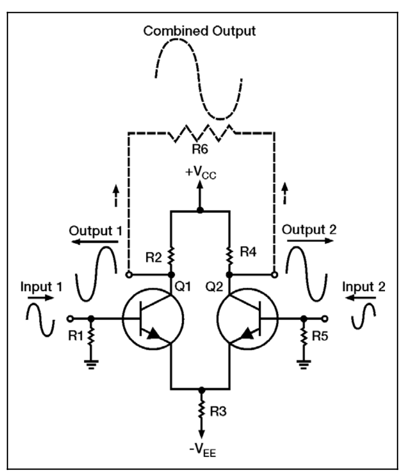
SINGLE-INPUT and a ***SINGLE-OUTPUT*** – a way a differential amplifier can be configured.



SINGLE-INPUT and a ***DIFFERENTIAL-OUTPUT*** – a way a differential amplifier can be configured.

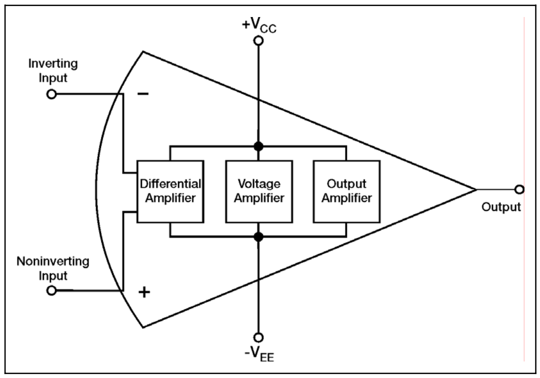


DIFFERENTIAL-INPUT and a ***DIFFERENTIAL-OUTPUT*** a way a differential amplifier can be configured.



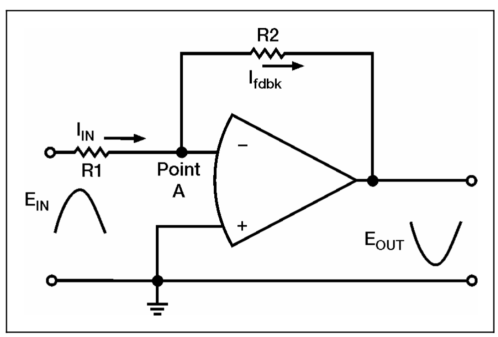
OPERATIONAL AMPLIFIER **-** an amplifier that has very high gain, very high input impedance, and very low output impedance. An operational amplifier is made from three stages:

- Differential amplifier.
- High-gain voltage amplifier.
- Output amplifier.

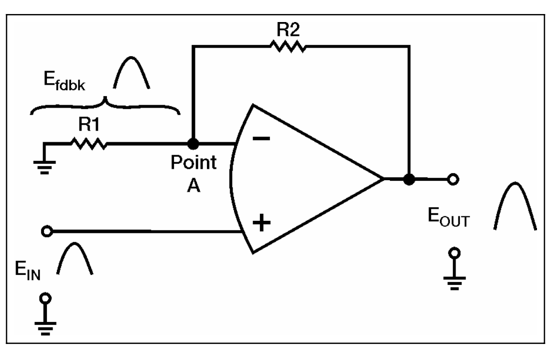


CLOSED-LOOP OPERATION – the way operational amplifiers are usually used. This means that degenerative feedback is used to lower the gain and increase the stability of the operational amplifier.

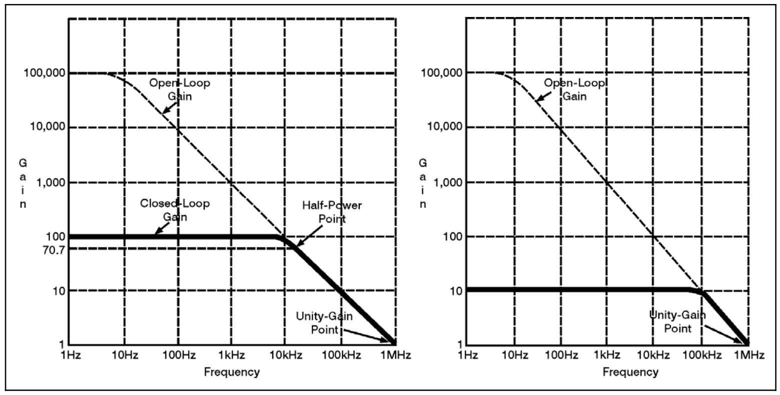
INVERTING CONFIGURATION – a way an operational amplifier circuit can be connected.



NONINVERTING CONFIGURATION – a way an operational amplifier circuit can be connected.

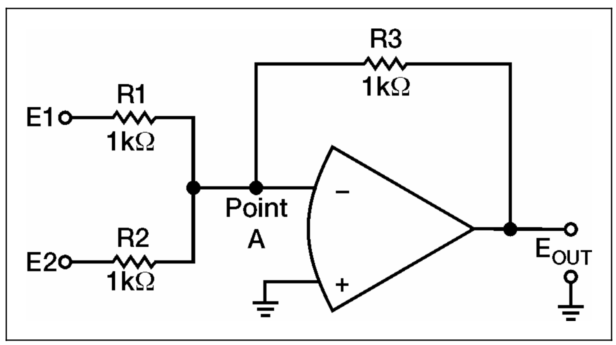


GAIN-BANDWIDTH PRODUCT – this is computed (for an operational amplifier) by multiplying the gain by the bandwidth (in hertz). For any given operational amplifier, the gain-bandwidth product will be remain the same regardless of the amount of feedback used.



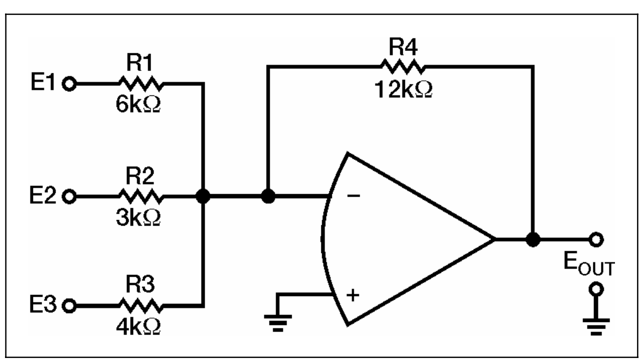
SUMMING AMPLIER - an application of an operational amplifier in which the output signal is determined by the sum of the input signals multiplied by the gain of the amplifier:

$$E_{OUT} = \text{gain}\,(E1 + E2)$$



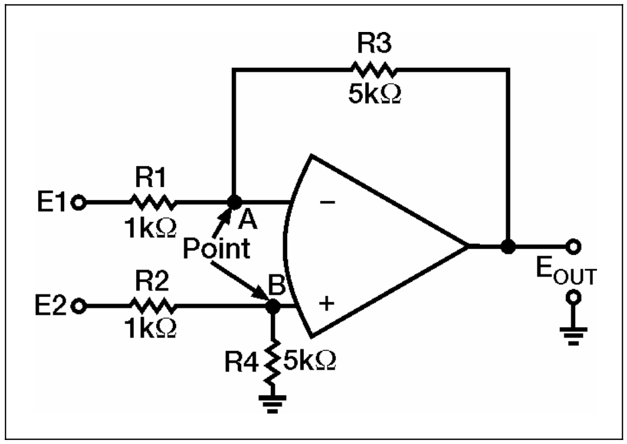
SCALING AMPLIFIER - a special type of summing amplifier with the output signal determined by multiplying each input signal by a different factor (determined by the ratio of the input-signal resistor and feedback resistor) and then adding these products:

$$E_{OUT} = [(\frac{R_{FDBK}}{R_{IN1}} \text{ x } E1) + (\frac{R_{FDBK}}{R_{IN2}} \text{ x } E2) + (\frac{R_{FDBK}}{R_{IN3}} + E3)]$$

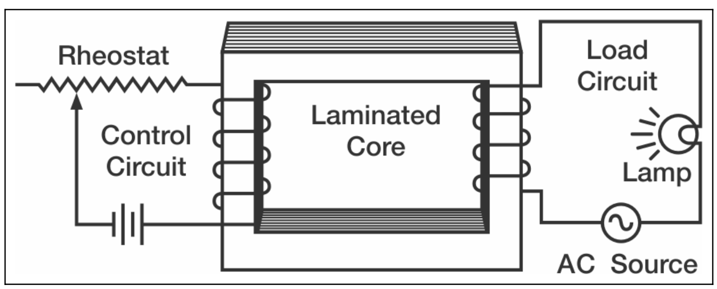


DIFFERENCE AMPLIFIER **-** an application of an operational amplifier in which the output signal is determined by the difference between the input signals multiplied by the gain of the amplifier:

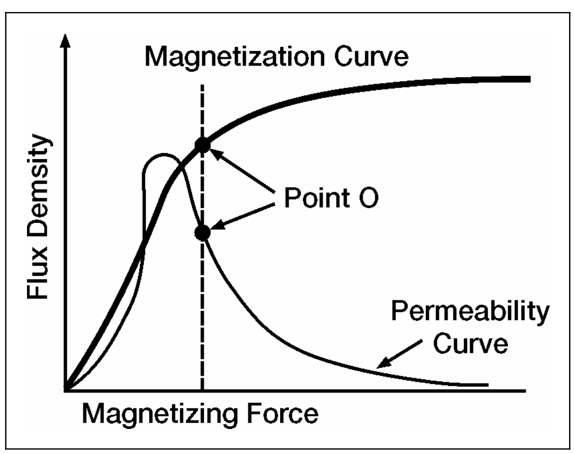
$$E_{OUT} = \text{gain}\,(E2 - E1)$$



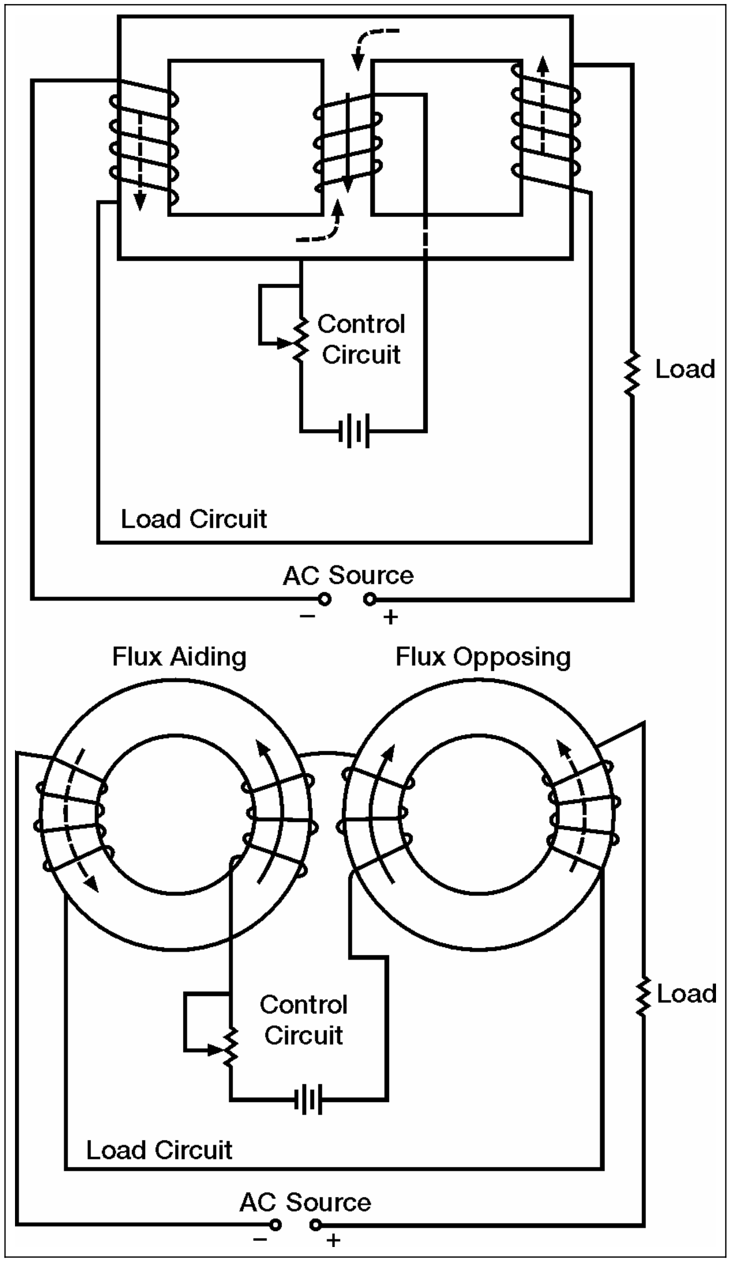
SATURABLE-CORE REACTOR **-** works upon the principle that increasing the current through a coil decreases the permeability of the core. The decreased permeability decreases the inductance of the coil that causes an increase in current (power) through the load.



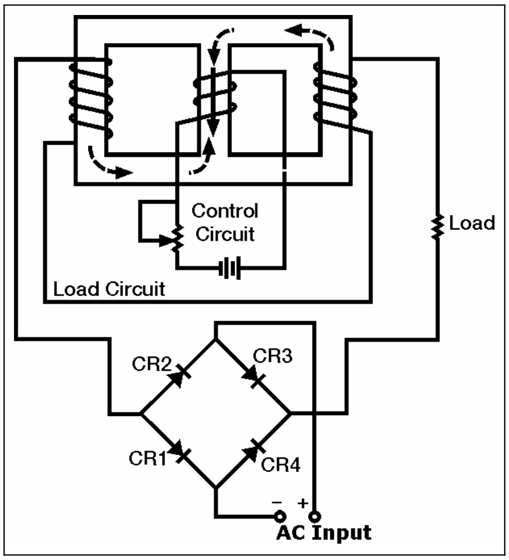
IDEAL OPERATING POINT **-** of a saturable-core reactor is on the KNEE OF THE MAGNETIZATION CURVE. At this point, small changes in control current will cause large changes in load current (power).



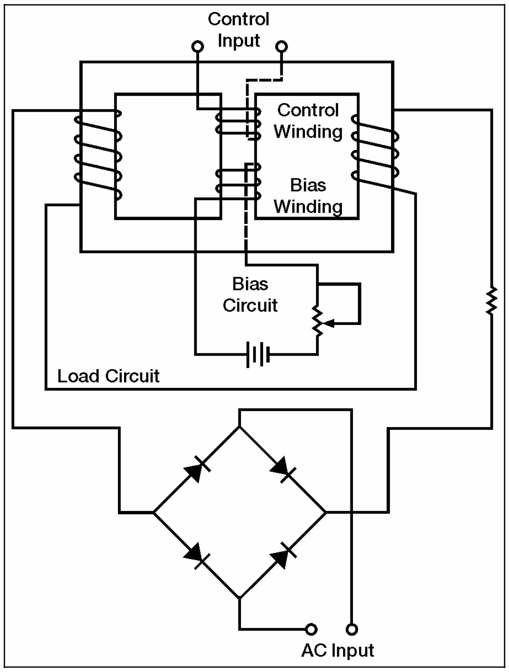
THREE-LEGGED and ***TOROIDAL SATURABLE-CORE REACTORS*** – these solve the problem of load flux aiding and opposing control flux during alternate half cycles of the AC load current.



MAGNETIC AMPLIFIERS **-** use the principle of electromagnetism to amplify signals. They are power amplifiers with a frequency response normally limited to 100 Hz or below. Magnetic amplifiers use a saturable-core reactor. A magnetic amplifier uses a RECTIFIER to solve the problem of HYSTERESIS LOSS in a saturable-core reactor.



BIAS WINDING **-** allows a DC bias voltage to be applied to the saturable-core reactor while AC control signals are applied to a separate control winding. In this way a magnetic amplifier can be set to the proper operating point.



CHAPTER 7
CHECK-ON-LEARNING QUESTIONS

When you are satisfied that you have answered every question to the best of your ability, check your answers using Appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. A differential amplifier can have how many input signals and/or output signals?

2. What is the one interesting aspect of an operational amplifier?

3. What is the name of the device that the magnetic amplifier uses to control an AC output signal?

4. A difference amplifier has how many outputs?

5. What is the name of the circuit when you combine the CB and CE configurations into a single transistor amplifier?

6. What is the secret to understanding any transistor amplifier circuit?

7. The output of the circuit remains at what constant when computing bias at any time period (T0 through T8)?

8. The gain of the differential amplifier (single-output) can be doubled by doing what?

9. When is the full potential of a circuit used?

10. Operational amplifiers were originally developed for what?

11. Why is the operational amplifier in such a widespread use?

12. What are the three most important characteristics of an operational amplifier?

13. What is the most common form of a operational amplifier?

14. How many stages are there within an operational amplifier?

15. An operational amplifier can be used with how many different input conditions (modes)?

16. Without feedback, the operational amplifier has what type of operation?

17. What is one result of degenerative feedback on operational amplifiers?

18. What is called when a point in a circuit is at ground potential (0 volts) but is not connected to ground?

19. What varies the gain of an operational amplifier?

20. What increases the bandwidth of an operational amplifier circuit?

21. What type of output will an adder circuit always produce?

22. A difference amplifier will produce an output based on the difference between what?

23. A magnetic amplifier has how many moving parts?

24. What does a magnetic amplifier use to control the power delivered to a load?

25. When does permeability change?

26. What is a ampere-turn?

27. What will increase if you increase the current through a coil?

28. What is the name of the portion of the magnetization curve where point "0" is located?

29. Adding a rectifier to the load circuit will do what two things?

30. What is the most effective way to apply bias to the saturable core and also allow AC input signals to control the magnetic amplifier?

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Appendix A

Check-on-Learning Answers

CHAPTER 1 (Semiconductor Diodes)

1. An electronic device that operates when electrons move within a solid piece of semiconductor material.

2. The resistance to electrical current flow decreases as temperature increases.

3. Commercial products, industry, and all branches of the armed services.

4. Three to four times.

5. Solid, liquid, and gaseous.

6. The atom.

7. Electrons, protons, and neutrons. The electron holds a negative charge, the proton holds a positive charge, and the neutron holds no electrical charge.

8. A valence shell.

9. An atom that has more than its normal amount of electrons and which acquires a negative charge.

10. Conduction band and valence band.

11. The width of the forbidden band or the separation between the conduction and valence bands.

12. The number of electrons in its valence shell.

13. Eight.

14. Covalent bond.

15. Electron current flow.

16. To increase the number of free charges that can be moved by an external applied voltage.

17. When added to a semiconductor material.

18. Any donor impurity having five valence electrons in its outer shell.

19. Makes use of the rectifying properties of a PN junction to convert AC into DC by permitting current flow in only one direction.

20. One.

21. Point-contact diode.

22. N-type material.

23. Positive holes.

24. Depletion region.

CHAPTER 1 (Semiconductor Diodes) (continued)

25. Negative.

26. Half-wave rectifier.

27. Any device that draws current.

28. It increases.

29. Metallic rectifier.

30. Forward biased.

31. Characteristic curve.

32. The limiting values of operating conditions which if exceeded could cause damage to a diode by either voltage breakdown or overheating.

33. Heat.

34. Only after you have made voltage and resistance measurements.

CHAPTER 2 (Transistors)

1. A transistor.

2. N and P materials.

3. Points out.

4. Point-contact transistors.

5. Quality control.

6. Observe the NPN or PNP elements that make up the transistor.

7. Making any electrical connections.

8. Electrons.

9. Emitter lead.

10. Holes.

11. They combine.

12. Minority.

13. Base-current path and collector-current path.

14. Amplifier.

15. Compensate for slight variations in transistor characteristics and changes in transistor conduction resulting from temperature irregularities.

16. Coupling capacitor.

17. The polarity of the source voltage.

18. Base-current bias (or fixed bias).

CHAPTER 2 (Transistors) (continued)

19. Self-bias.

20. To prevent amplitude distortion.

21. Voltage-divider type.

22. Class A amplifier operation.

23. Push-pull.

24. Amount of bias and the amplitude of the input signal.

25. Two.

26. Common emitter (CE), common base (CB), and common collector (CC).

27. Common emitter.

28. BETA.

29. Common base.

30. ALPHA.

31. Common collector (CC).

32. 2 to 500.

33. 50 to 1,500.

34. The kind of transistor, some of the common applications for the transistor, and general sales features.

35. Number of junctions.

36. Ohmmeter or transistor testor.

37. Substitution.

38. The electrostatic discharge from the human body.

39. How the transistor is mounted.

40. Gain and leakage.

41. A normal gain for an audio-frequency transistor.

42. Hybrid and Monolithic.

CHAPTER 3 (Special Devices)

1. Minority carriers.

2. Zener Effect and Avalanche Effect.

3. Zener Effect.

4. Forbidden Energy Band or Forbidden Gap.

CHAPTER 3 (Special Devices) (continued)

5. An external series current-limiting resistor.

6. Voltage regulators.

7. Quantum-mechanical tunneling.

8. Zero.

9. Negative resistance region.

10. Depletion region.

11. Bias.

12. It decreases.

13. Allows a DC voltage to be used.

14. A switch that can turn on or off small or large amounts of power.

15. Four.

16. AC.

17. SCR.

18. Both.

19. Forward biased.

20. 1.6 volts.

21. Negative.

22. High.

23. Reverse bias.

24. 1:1,000.

25. Photovoltaic Cell (Solar Cell).

26. One.

27. Resistor.

28. Voltage gradient.

29. The manufacturer.

30. Voltage.

31. The gate.

32. N-channel and P-channel.

33. Effective cross-sectional area of the channel.

34. Five.

35. Pinch-off.

CHAPTER 3 (Special Devices) (continued)

36. Its input impedance is significantly higher.

37. A positive gate voltage.

38. Higher.

39. Depletion mode or enhancement mode.

40. Gate, drain, substrate, source.

41. Whether it is a P-channel type or N-channel type.

42. Avoid accidental damage.

CHAPTER 4 (Solid State Power Supplies)

1. Transformer, Rectifier, Filter, Regulator.

2. Converts the AC input signal to a pulsating DC voltage.

3. Converts pulsating DC to a purer, more desirable form of DC voltage.

4. Maintains the output of the power supply at a constant level in spite of large changes in load current or input line voltages.

5. Half-wave rectifier.

6. Higher.

7. 60 Hz.

8. Peak voltage is only half the peak voltage in the half-wave rectifier.

9. Bridge Rectifier.

10. Produces nearly twice as much voltage output.

11. Higher.

12. Substantially pure DC.

13. Decrease.

14. Electromagnetic field.

15. Parallel.

16. Rate of discharge.

17. Double the frequency of the rectifier.

18. Twice.

19. From 1 to 20 henries.

CHAPTER 4 (Solid State Power Supplies) (continued)

20. A full-wave rectifier.

21. The inductor.

22. Correct polarity.

23. To hold the ripple to an absolute minimum.

24. LC capacitor-input filter.

25. More expensive and its larger size.

26. Low DC output voltage.

27. Constant voltage.

28. Voltage regulator.

29. Variation.

30. Series and Shunt.

31. Blocks current.

32. Provides a constant current regardless of changes in the input voltage or load current.

33. 1,000 volts to 30,000 volts.

34. Better voltage regulation.

35. Two.

36. The pass transistor is in series with the load.

37. So the load being supplied by the power supply can be wired directly to the metal chassis.

38. Visual and Signal Tracing.

CHAPTER 5 (Amplifiers)

1. The process of providing an increase in amplitude.

2. A device that enables an input signal to control an output signal.

3. To provide various amounts of signal amplification.

4. Function and Frequency Response.

5. Power amplifier.

6. Characteristics of the input and output signals.

7. Wide-band amplifiers.

8. Current-control.

9. The amount of time (in relation to the input signal) that current flows in the output circuit.

10. Class A, Class B, Class AB, and Class C.

CHAPTER 5 (Amplifiers) (continued)

11. Class B amplifier.

12. The transistor does not conduct except during a small portion of the input signal.

13. The signal increases and the final output is increased.

14. Coupling.

15. Direct, RC, Impedance, and Transformer.

16. Power supply requirements.

17. RC coupling.

18. Transformer coupling.

19. Power.

20. Divide the signal voltage by the signal current.

21. The process of sending part of the output signal of an amplifier back to the input of the amplifier.

22. Positive and Negative.

23. Amount of the input signal.

24. CE configuration.

25. Base-to-emitter bias.

26. Remove the signal from the emitter.

27. Negative feedback.

28. Frequency response.

29. A device that produces two signals that differ in phase from each other from a single-input signal.

30. CE and common-collector.

31. To provide input signals to a single-stage amplifier that uses two transistors.

32. Class A and Class B.

CHAPTER 6 (Video and Radio Frequency Amplifiers)

1. 10 KHz and 100,000 KHz.

2. Performance of an amplifier at various frequencies.

3. The frequency response of the amplifier.

4. The amount of “width” of frequencies or the band of frequencies that the amplifier is most effective in amplifying.

CHAPTER 6 (Video and RF Amplifiers) (continued)

5. Points at which the output voltage (or current) is 70.7 percent of the maximum output voltage (or current).

6. The resistance of the circuit.

7. Reactive elements (capacitance and inductance) in the circuit.

8. Resistors.

9. Negative (degenerative).

10. Capacitance of an amplifier and the interelectrode capacitance of the transistor.

11. Decreases.

12. Increases.

13. Inductors.

14. The use of a peaking coil in series with the output signal path.

15. Shunt peaking.

16. Combination peaking.

17. Capacitance (or capacitive reactance).

18. Input signals.

19. Input and output voltage.

20. Increases.

21. A circuit that provides the desired response at a particular frequency.

22. Tuned.

23. Variable capacitors.

24. To broaden the bandpass.

25. The amount of energy transferred from the primary to the secondary of the transformer.

26. Optimum.

27. Compensation.

28. The realignment of the magnetic domains in the core of the transformer each time the polarity of the magnetic field changes.

29. The signal.

30. Neutralization.

31. Positive feedback.

32. Negative (degenerative).

CHAPTER 7 (Special Amplifiers)

1. Two.

2. It can perform mathematical operations electronically.

3. Saturable-core reactor.

4. One.

5. Two-input, single-output, difference amplifier.

6. The collector current is controlled by the base-to-emitter bias.

7. Zero.

8. Taking the output signal between the two output terminals.

9. When a differential amplifier is connected with a differential input and a differential output.

10. Analog (non-digital) computers and to perform mathematical functions.

11. It is very versatile and efficient device.

12. Very high gain; very high input impedance; and very low output impedance.

13. Integrated chip.

14. Three.

15. Three.

16. Open-loop.

17. The inverting and noninverting inputs to the operational amplifier will be kept at the same potential.

18. Virtual ground.

19. Frequency.

20. Degenerative feedback.

21. One that is equal to the sum of the input signals but opposite in polarity.

22. Input signals.

23. None.

24. Changing inductance.

25. When the magnetizing force changes until saturation is reached.

26. The magnetomotive force developed by 1 ampere of current flowing in a coil of one turn.

27. Ampere-turns.

28. Knee of the curve.

29. Eliminate the hysteresis loss and increase the gain.

30. Bias winding.

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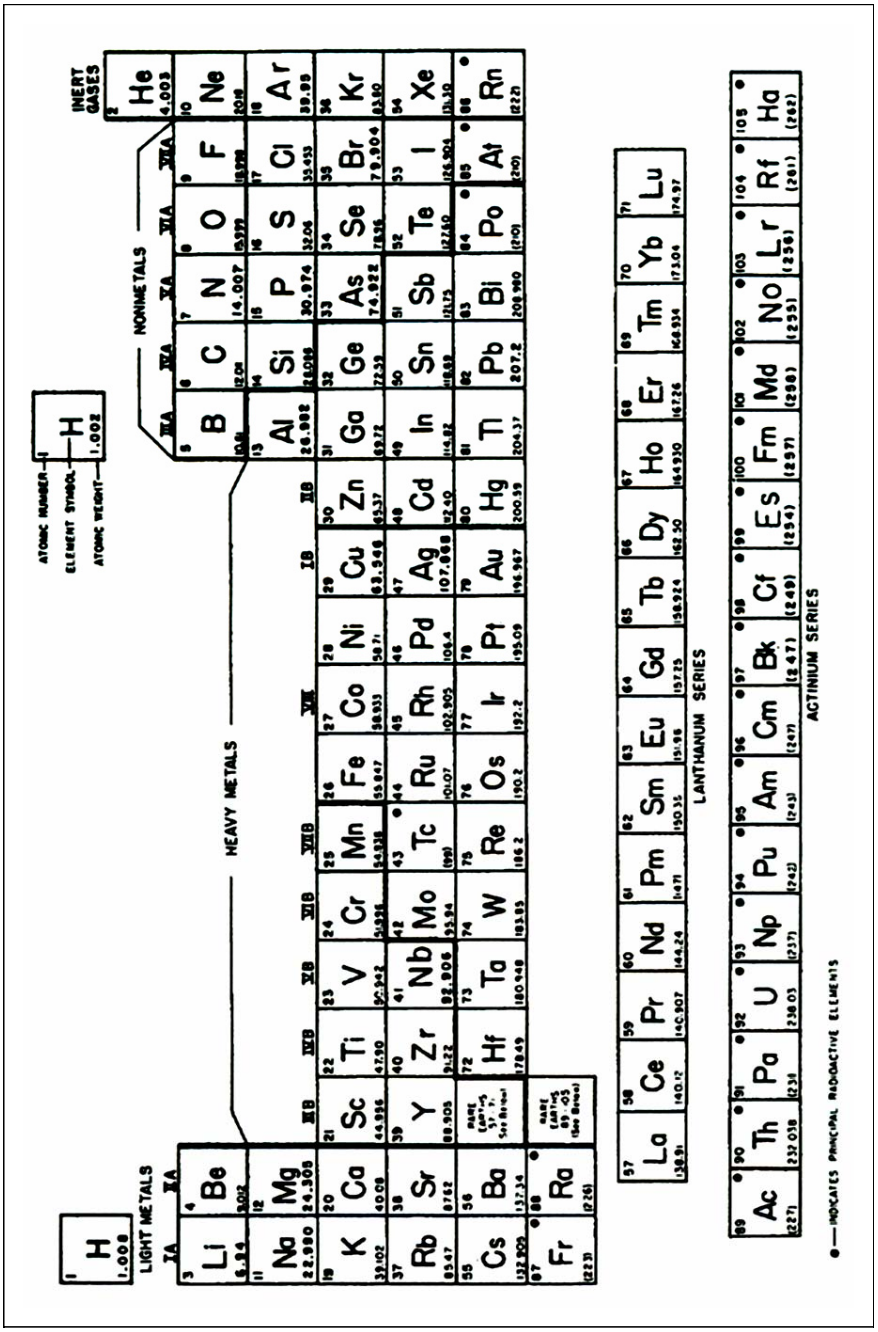
Appendix B

Periodic Table of Elements



NOTE: See pages B-2 through B-5 for interpretation of symbols.

Symbol	Name	Atomic Number	Atomic Weight
Ac	Actinium	89	1(227)
Ag	Silver	47	107.868
Al	Aluminum	13	26.982
Am	Americium	95	(243)
Ar	Argon	18	39.95
As	Arsenic	33	74.922
At	Astatine	85	(210)
Au	Gold	79	196.967
B	Boron	5	10.81
Ba	Barium	56	137.34
Be	Beryllium	4	9.012
Bi	Bismuth	83	208.980
Bk	Berkelium	97	(247)
Br	Bromine	35	79.904
C	Carbon	6	12.011
Ca	Calcium	20	40.08
Cd	Cadmium	48	112.40
Ce	Cerium	58	140.12
Cf	Californium	98	(249)
Cl	Chlorine	17	35.453
Cm	Curium	96	(247)
Co	Cobalt	27	58.933
Cr	Chromium	24	51.996
Cs	Cesium	55	132.905
Cu	Copper	29	63.546
Dy	Dysprosium	66	162.50
Es	Einsteinium	99	(254)
Er	Erbium	68	167.26
Eu	Europium	63	151.96

Symbol	Name	Atomic Number	Atomic Weight
F	Fluorine	9	18.998
Fe	Iron	26	55.847
Fm	Fermium	100	(257)
Fr	Francium	87	(223)
Ga	Gallium	31	69.72
Gd	Gadolinium	64	157.25
Ge	Germanium	32	72.59
H	Hydrogen	1	1.008
Ha	Hahnium	105	(262)
He	Helium	2	4.003
Hf	Hafnium	72	178.49
Hg	Mercury	80	200.59
Ho	Holmium	67	164.930
I	Iodine	53	126.904
In	Indium	49	114.82
Ir	Iridium	77	192.2
K	Potassium	19	39.102
Kr	Krypton	36	83.80
La	Lanthanum	57	138.91
Li	Lithium	3	6.94
Lr	Lawrencium	103	(256)
Lu	Lutetium	71	174.97
Md	Mendelevium	101	(258)
Mg	Magnesium	12	24.305
Mn	Manganese	25	54.938
Mo	Molybdenum	42	95.94

Symbol	Name	Atomic Number	Atomic Weight
N	Nitrogen	7	14.007
Na	Sodium	11	22.990
Nb	Niobium	41	92.906
Nd	Neodymium	60	144.24
Ne	Neon	10	20.18
Ni	Nickel	28	58.71
No	Nobelium	102	(255)
Np	Neptunium	93	(237)
O	Oxygen	8	15.999
Os	Osmium	76	190.2
P	Phosphorus	15	30.974
Pa	Protactinium	91	(231)
Pb	Lead	82	207.2
Pd	Palladium	46	106.4
Pm	Promethium	61	(147)
Po	Polonium	84	(210)
Pr	Praseodymium	59	140.907
Pt	Platinum	78	195.09
Pu	Plutonium	94	(242)
Ra	Radium	88	(226)
Rb	Rubidium	37	85.47
Re	Rhenium	75	186.2
Rf	Rutherfordium	104	(261)
Rh	Rhodium	45	102.905
Rn	Radon	86	(222)
Ru	Ruthenium	44	101.07

Symbol	Name	Atomic Number	Atomic Weight
S	Sulfur	16	32.06
Sb	Antimony	51	121.75
Sc	Scandium	21	44.956
Se	Selenium	34	78.96
Si	Silicon	14	28.086
Sm	Samarium	62	150.35
Sn	Tin	50	118.69
Sr	Strontium	38	87.62
Ta	Tantalum	73	180.948
Tb	Terbium	65	158.924
Tc	Technetium	43	(99)
Te	Tellurium	52	127.60
Th	Thorium	90	232.038
Ti	Titanium	22	47.90
Tl	Thallium	81	204.37
Tm	Thulium	69	158.934
U	Uranium	92	238.03
V	Vanadium	23	50.942
W	Tungsten	74	183.85
Xe	Xenon	54	131.30
Y	Yttrium	39	88.905
Yb	Ytterbium	70	173.04
Zn	Zinc	30	65.37
Zr	Zirconium	40	91.22

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Glossary

α	alpha
A.C.	alternating current
AC	alternating current
AM	amplitude modulation
AS	arsenic
ATTN	attention
β	beta
BW	bandwidth
C-E	communications-electronics
C	Celsius; capacitance
CB	common base
C_{BC}	base-to-collector capacitance
C_{BP}	bypass capacitor
CC	common collector
C_C	coupling capacitor
CE	common emitter
C_{EB}	emitter-to-base capacitance
cemf	counterelectromotive force
C_{IN}	input capacitance of the next stage
C_{OUT}	output capacitance of the circuit
CRT	cathode-ray tube
C_T	total capacitance of the circuit
D.C.	District of Columbia; direct current
DA	Department of the Army
DC	direct current
E	voltage
E_{avg}	average voltage
E_{fdbk}	voltage feedback signal
E_{IN}	input voltage
E_{max}	maximum voltage
E_{OUT}	output voltage

E_{peak}	peak voltage
E_r	ripple voltage
E_{rms}	root mean square voltage
E_R	ripple component
E_{R1}	input of circuit number 1
E_{R2}	input of circuit number 2
E_S	AC source
ETM	electronic technical manual
f	frequency
F	Fahrenheit
FDN	frequency-determining network
FET	field-effect transistor
FM	field manual
GE	germanium
H_{fb}	hybrid, forward, CB configuration
H_{fe}	hybrid, forward, emitter
HQ	headquarters
Hz	hertz
I	current
I_B	base current
I_C	collector current
IC	integrated circuit
ICB	integrated circuit board
ID	identification
I_D	drain current
I_E	emitter current
IF	intermediate frequency
I_FA_V	average rectifier forward current
I_{fdbk}	feedback current
IGFET	insulated gate field effect transistor
I_L	inductance current
I_{max}	maximum current
I_N	indium

I_P	peak current
I_R	reverse current
I_{RAV}	average reverse current
I_{SURGE}	peak surge current
I_T	total current
I_V	valley current
∞	infinite
JAN	Joint Army-Navy
JFET	junction field-effect transistor
k	kilo- (thousand)
KHz	kilohertz
L	inductance
LC	inductance-capacitor
LED	light emitting diode
M	meter(s)
MA	milliammeter
mA	milliamperes
Max	maxiumum
mH	millihenries
MHz	megahertz
MOSFET	metal oxide semiconductor field effect transistor
mV	millivolt(s)
mW	milliwatt(s)
N-channel	negative channel
N-material	negative material
N-region	negative region
N-type	negative-type
No.	number
NPN	Not Pointing iN
N_P	number of turns in the primary
N_S	number of turns in the secondary
Ω	ohms
%	percent

P	power
P-channel	positive channel
P-material	positive material
P-region	positive region
P-type	positive-type
PCB	printed circuit board
pF	picofarad
PN	positive, negative
PNP	Points iN
pps	pulses per second
$\mathbf{P_{R1}}$	output of circuit number 1
$\mathbf{P_{R2}}$	input to circuit number 2
PRV	peak reverse voltage
R	resistance
$\mathbf{R_B}$	bias resistor
RC	resistor-capacitor
RF	radio frequency
RFC	radio frequency choke
$\mathbf{R_L}$	load resistor
RMS	root mean square
$\mathbf{R_{Q1}}$	transistor resistance
$\mathbf{R_S}$	fixed resistor
$\mathbf{R_T}$	maximum resistance
$\mathbf{R_V}$	regulating device
SCR	silicon controlled rectifiers
SW	switch
T0	time zero
T1	time one
T2	time two
T3	time three
T4	time four
T5	time five
T6	time six
T7	time seven

T8	time eight
t	time
TC	training circular
TM	technical manual
TRADOC	Training and Doctrine Command
T_{RR}	reverse recovery time
TV	television
UJT	unijunction transistor
US	United States
V	volt(s)
VA	Virginia
VAC	volts alternating current
V_{BB}	base voltage supply
V_C	collector voltage
V_{CC}	collector voltage supply
VDC	volts direct current
V_{DD}	drain supply
V_{EE}	emitter voltage supply
$V_F A_V$	average forward voltage drop
$V_F @ I_F$	maximum forward voltage drop at indicated forward current
V_{GG}	gate-source voltage
VHF	very high frequency
V_R	DC blocking voltage
VT	vacuum tube
W	watt(s)
X_C	capacitive reactance
X_L	inductive reactance
γ	gamma
Z	impedance
Z_P	impedance of the primary
Z_S	impedance of the secondary

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TC 9-62
23 JUNE 2005

By Order of the Secretary of the Army:

PETER J. SCHOOMAKER
General, United States Army
Chief of Staff

Official**:**

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